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BIDIRECTIONAL REFLECTANCE DISTRIBUTION (BRDF) OF NASA SHUTTLE TILES

R. P. Young and B. E. Wood
Calspan Corporation/AEDC Operations

April 1991

Final Report for Period January 2 - January 18, 1991

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ARNOLD ENGINEERING DEVELOPMENT CENTER
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This report has been reviewed and approved.

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13. ABSTRACT (Maximum 200 words)

The report describes the apparatus and method used to measure the BRDF of both black and white, flown and unflown, NASA space shuttle tiles. The measured data are included in the report appendix.

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NOMENCLATURE

A_s	Illuminated Area on Test Sample, cm^2
BRDF	Bidirectional Reflectance Distribution Function, sr^{-1}
DELTA L	Difference between Filter Cut-off and Cut-on Wavelength, µm
H_i	Incident Irradiance, W cm^{-2}
N_r	Reflected Radiance, W cm^{-2} sr^{-1}
L_1	Filter Cut-on Wavelength, µm
L_2	Filter Cut-off Wavelength, µm
L_c	Filter Center Wavelength, µm
P_i	Incident Power, W
P_s	Power Collected at Detector from Test Sample, W
R	Detector Resposivity, volts/W
V_D	Detector Output when Viewing Diffuser, volts
V_s	Detector Output when Viewing Test Sample, volts
Ω	Detector Collection Solid Angle, sr
Θ	Angle Referenced to the Surface Normal, degree
ρ_D	Reference Diffuser Reflectivity

1.0 INTRODUCTION

The work reported herein was conducted by the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), under Program Element 921F01, Control Number 9F01, at the request of the Geophysics Laboratory (GL), Hanscom Air Force Base, Mass. The GL Project and Test Program Manager was Dr. Edmund Murad. Funding for this work was provided by GL. The test results were obtained by Calspan Corporation/AEDC Operations, operating contractor for the Aerospace Flight Dynamics Testing effort at AEDC, AFSC, Arnold Air Force Base, Tennessee. The tests were conducted in the BRDF Measurements Laboratory of the Aerospace Systems Facility (ASF) during the period from January 2 to January 18, 1991, under AEDC Project Number CQ50VV.

Ground based infrared (IR) cameras, located on a Maui mountaintop, are used to support a series of experiments associated with studying the condition of space shuttle tiles while in flight. This includes studying the reflective properties of the shuttle tiles while the shuttle is in orbit. The IR cameras used in these experiments are sensitive in the 2.0- to 5.5-μm wavelength range; therefore the shuttle tile optical properties are required for this same spectral range. The optical property of particular interest is the tile Bidirectional Reflectance Distribution Function (BRDF). The tile BRDF is input into radiation models to help predict the expected power levels observed by the IR cameras. The objective of the tests reported herein was to measure the tile BRDF over the range of 2.0- to 5.5-μm as a function of the reflectance angle. The BRDF of both black and white (flown and un-flown) shuttle tiles were measured.

The final data package from the tests was incorporated into this Test Summary Report (TSR) as an Appendix and was previously transmitted to GL. Requests for copies of the data should be directed to Spacecraft Environment Branch, GL/PHK, Hanscom AFB, MA 01730.

The purpose of this report is to document the test and to describe the test parameters. This report provides information to facilitate interpretation of the data, but does not include any discussion of results or data analysis.

2.0 APPARATUS

2.1 TEST FACILITY

The BRDF test equipment (Fig. 1) was mounted on a 5- by 10-ft optical table located in a large, down-flow clean room in the Mark 1 building. The test setup included a source assembly, chopper, flat folding mirror, focusing mirror, test sample support assembly, rotary arm assembly, and an Infrared (IR) detector. The source assembly (Fig. 2) was an Optronics Laboratories IR source attachment (Model 740-20IR) for a Model 746 Spectoradiometer. It contained an IR (Nernst) glower and a

150- w quartz halogen visible source, either of which could be selected by rotation of the spherical imaging mirror. The IR glower was operated at nominally 1,000 C. The spectral radiance of a 1,000 C blackbody is presented in Fig. 3. The selected source lamp was imaged at the source assembly output aperture by the spherical mirror. The source assembly output aperture was rectangular in shape (0.18 X 0.3 in.). A Stanford Research Systems Model SR540 variable speed optical chopper was mounted at the source assemble output aperture. The chopper was operated at 300 Hz.

The source output was directed toward an 8-in.-diam, 40-in. focal length re-imaging mirror (Fig. 4) by a flat folding mirror. The large mirror re-imaged the source aperture at the detector (Fig. 1). Both mirrors were mounted in 2-axis gimbaled mounts to facilitate optical alignment. The source beam incident on the test sample was slightly elliptical (nominally 1.1 in. in diameter).

The test samples were mounted on a mounting assembly (Fig. 5) that had 4 deg of freedom, 2 in translation and 2 in rotation. The sample assembly could be translated along the optical axis to accommodate different sample thicknesses. Translation perpendicular to that axis was provided to center the sample mount relative to the optical beam. The rotational adjustments were used to align the test sample surface normal relative to the incident radiation. The sample mount was designed to accept 2-in.-diam test samples. Three cylindrical test samples are shown in Fig. 5. The NaCl (in sample mount) and flame sprayed aluminum test samples were diffuse reflectance references. The flame sprayed aluminum sample was used as the reference reflector for all data presented in the final data package (Appendix). Its surface reflectance as a function of wavelength is presented in Fig. 6 (reflectance data provided by Surface Optics Corporation). The flat mirror was used during system alignment. The tile sample adaptor (the large square plate shown in Fig. 5) was used to mount the tile samples.

The scattered energy reflected from the test samples was measured using an InfaRed Associates photovoltaic Indium Antimonide (InSb) detector (Fig. 7). The spectral detectivity of the detector is shown in Fig. 8. The detector was mounted within a dewar assembly with a sapphire window. The detector was 4-mm-diam and operated at 77 K. The detector was operated in the current mode. Its output was measured using a low noise Field Effects Transistor (FET) input and a Transimpedance Amplifier (TIA) designed and fabricated at AEDC. The TIA feedback resistance was 10 K. Bandpass filters for spectral measurements were mounted over the dewar window. Optical properties of the bandpass filters are provided in Table 1.

The detector dewar was mounted on the rotary arm assembly (Fig. 9). The assembly included an Aerotech, Inc., motor driven rotary stage (Model ARS 304) and an aluminum bar. The aluminum bar was supported on its free end with a low friction slide. The rotational resolution was 120 motor steps per 1 deg of stage rotation. The detector to test sample distance was nominally 9.8 in.

2.2 TEST ARTICLES

The test articles were samples of NASA space shuttle orbiter thermal protection tiles (Fig. 10). Four tile samples were used for this measurements program. Two of the tiles were white and two were black. One each of the white and black tiles were flown on past shuttle orbiter missions and two were not flown. Tiles were identified as follows:

Sample 1: BLACK HRSI TILE
V070-391061-172
FLOWN ON CHALLENGER
AEDC IDENTIFICATION: FLOWN BLACK

Sample 2: BLACK HRSI TILE
V070-391061-1452
UNFLOWN
AEDC IDENTIFICATION: UNFLOWN BLACK

Sample 3: WHITE LRSI TILE
V070-297309-084
FLOWN ON COLUMBIA
AEDC IDENTIFICATION: FLOWN WHITE

Sample 4: WHITE LRSI TILE
V070-394017-032
UNFLOWN
AEDC IDENTIFICATION: UNFLOWN WHITE

Figures 10b, c, d, and e are individual photographs of each of the above tile samples. The white tiles were 8-in. square and 1/2-in. thick. The black samples were 6-in. square and 1.5-in. thick.

2.3 TEST INSTRUMENTATION

The BRDF measurements system instrumentation included a chopper motor controller, a detector (TIA) voltage measurement instrument, and a rotary stage motor drive controller. The SR540 optical chopper drive unit provided the chopper motor power, chopper frequency readout, and a reference signal at the same frequency as the chopped optical signal. The TIA output voltage was measured using a Stanford Research (Model SR530) phase lock amplifier. The reference signal from the chopper drive controller was the reference signal for the SR530. The TIA was powered from a ± 12-volt power supply (four 6-volt batteries). The rotary stage stepping motor was driven using an Aerotech stepping motor drive (Model SA1401). The number of steps input to the rotary stage drive motor (for a desired drive increment) was selected by thumb wheel switches on the front of the controller.

3.0 TEST DESCRIPTION

3.1 TEST PROCEDURES

The tile BRDF measurements were taken in sets of ten for each wavelength. After the system alignment was completed, test runs were made in the following order: (1) NaCl diffuser, (2) aluminum diffuser, (3) unflown white left, (4) unflown white right, (5) flown white left, (6) flown white right, (7) unflown black left, (8) flown black left, (9) flown black right, and (10) another aluminum diffuser. Data were not recorded for unflown black right because that area of the black tile was marked with a red dye.

The alignment procedure started by positioning the rotary arm at 5 deg from the test sample normal. The desired optical filter was installed on the detector dewar. The flat test mirror was installed in the sample holder and its surface was centered over the center of the rotary arm alignment pin. The visible source was selected and the visible beam was centered vertically on the test mirror using the large mirror vertical gimbal adjustments. The visible beam was centered horizontally over the rotary arm alignment pin using the large mirror horizontal gimbal adjustment. The test mirror gimbal was then used to position the source image at a marked reference position on the detector dewar. The angle of incidence of the optical beam relative to the mirror surface normal was nominally 9 deg. However, the angle of incidence for the tile samples was dependent on the parallelism of the tile front and back surfaces.

The mirror sample was then replaced with the NaCl diffuser. The NaCl diffuser surface was aligned over the rotary stage axis of rotation. The visible source was turned off and the IR source was selected. The IR source was allowed nominally a 15-min warm up. After the phase lock amplifier was properly adjusted, the detector signal was recorded for that angular position. The rotary arm was moved to the next angular position and the detector output again recorded. The sequence of moving the rotary arm and recording the detector signal was repeated until the rotary arm was 34 deg from the test surface normal. That concluded the series of measurements for one test run.

The NaCl diffuser was removed from the sample holder and the aluminum diffuser installed. The rotary arm was rotated back to the start position (5 deg from the surface normal). The sequence of recording the detector output and moving th e rotary arm was repeated. The aluminum diffuser was removed and the rotary arm moved back to the start position. The tile adapter was installed in the test sample mount. The unflown white tile was installed in the sample adapter (identification number up). The left edge was positioned so that the illuminated spot on the tile was 2.25 in. from the left edge of the tile. The vertical spot position was 2.25 in. from the bottom of the tile for all tile measurement Detector signal versus arm rotary position was recorded using the same procedure as

was used to measure the scattered radiation from each of the diffuser samples. The tile sample was then translated in the tile adapter so that the illuminated spot was 2.13 in. from the right edge of the tile and the measurements repeated. This same procedure was used for the flown white tile and for both black tiles with the following exceptions. Only the left side of the unflown black tile was measured. The illuminated spot for the unflown black tile was 1.8 in. from the tile's left edge. The illuminated spots for the flown black sample were 2.1 in. from the left and right edges. After the tile measurements were completed, the aluminum diffuser run was repeated. This completed one test set of 10 runs. The entire test alignment and measurement procedure was performed for each optical filter and for the 0- to 5.5-µm (no filter) test runs.

3.2 DATA REDUCTION

The Bidirectional Reflectance Distribution Function (BRDF) for an opaque surface was defined in Ref. 1 for the general case of a surface illuminated by a distant source as:

$$BRDF = \frac{dN_r}{dH_i} \tag{1}$$

where N_r is the radiance reflected from the reflecting surface and H_i is the irradiance incident on the reflecting surface. The distance of the source of radiation to the reflecting surface was nominally nine times the diameter of the source aperture, thus the distant source assumption was approximated. The area illuminated on the reflecting test sample was small in comparison to the distance between the detector and test surface; therefore, the differential notation can be dropped. Equation (1) then becomes:

$$BRDF = \frac{N_r}{H_i} \tag{2}$$

The irradiance (H_i) on the test surface is defined by the power (P_i) and the test sample illuminated area (A_s).

$$H_i = \frac{P_i}{A_s} \tag{3}$$

The power incident on the test surface was determined from the detector signal recorded from the energy reflected from a reference diffuser (flame sprayed aluminum).

$$V_D = \frac{\rho_D P_i \Omega R (COS\Theta_r)_D}{\Pi} \tag{4}$$

or

$$P_i = \frac{V_D \Pi}{\Omega R \rho_D (COS\Theta_r)_D} \tag{5}$$

The subscript (D) refers to the diffuser. The incident irradiance was calculated from the average detector signal of six samples of data taken at one degree increments from 5 to 10 deg from the surface normal. Note that values for the collection solid angle and detector responsivity were not needed because they cancel in the final BRDF equation.

The power collected by the detector viewing the test surface (P_S) is:

$$P_s = N_r \Omega A_s COS\Theta_r \tag{6}$$

Solving Eq. (6) for Nr gives:

$$N_r = \frac{P_s}{\Omega A_s COS\Theta_r} \tag{7}$$

Substituting Eqs. (3) and (7) into Eq. (2) gives:

$$BRDF = \frac{P_s}{P_i \Omega COS\Theta_r} \tag{8}$$

Scattered power from the test sample is:

$$P_s = \frac{V_s}{R} \tag{9}$$

Substituting Eqs. (5) and (9) into Eq. (8) gives:

$$BRDF = \frac{V_s \rho_D (COS\Theta_r)_D}{\Pi V_i COS\Theta_r} \tag{10}$$

Equation (10) defines the test sample BRDF in terms of the parameters measured by the scatterometer data acquisition system. Note that $V_D/(COS\Theta_r)_D$ was a single valued parameter (the average of six angular measurements as defined previously).

3.3 UNCERTAINTY/PRECISION OF MEASUREMENTS

The BRDF of a test sample was not a measured quantity, but was a calculated function dependent on the reference diffuser reflectivity and the output of an IR detector that viewed the illuminated diffuser and the test sample surfaces. Errors in the measured quantities propagate to the BRDF through the functional relationship as presented in Eq. (10). The effect of the propagation was approximated by the Taylor series method. It should be noted that the detector output voltage from the diffuse and test samples was used as a voltage ratio, and that the dynamic range of the voltage ratio was relatively low for these tests. Stray radiation contributions to BRDF measurements errors were not significant for the tile BRDF measurements reported herein because of the relatively high scatter from the test sample surfaces.

The uncertainty of the BRDF measurements, resulting from the uncertainty of the measured parameters, was nominally 5 percent. The fact that the reference diffuse reflector was not perfectly Lambertian was not included in the above uncertainty value. It was estimated that the non-Lambertian characteristic of the reference diffuser accounted for an additional 5-percent uncertainty in the BRDF measurements. The total uncertainty in the BRDF measurements was less than 10 percent.

The angular position of the rotary arm, as measured relative to the test surface normal, was established using an alignment mirror. The uncertainty of this angular alignment was less than ± 0.1 deg. However, the actual angle from the front surface of a test sample was dependent on the parallelism of the front and back surfaces. For test tiles having a visible specular reflection lobe, the error in angular measurement can be determined by the angular location of the peak BRDF value. The angular position error, based on the location of the peak BRDF value, was estimated to be ± 0.5 deg.

4.0 DATA PRESENTATION

The final data package included in the Appendix of this report contains a contents page, tabulated BRDF results, and plots of test sample BRDF as a function of angle measured from the surface normal. A sample tabulation and plots of the BRDF data are presented in Table 2 and Fig. 11, respectively.

4.1 BRDF TABULATIONS

Table 2 is a sample of the tabulated data included in the Appendix. The header record includes the computer file number, the test sample identification, the diffuse reference standard, and a note to indicate that the angular reference is the test sample surface normal. The first data column is the scatter angle (degrees) as measured from the surface normal, followed by nine columns of BRDF data (sr^{-1}). The first and last BRDF data columns were measured with the detector unfiltered

(0 to 5 μm). The other columns are spectral BRDF values. The optical filter center wavelength is the number just below the run number.

4.2 BRDF PLOTS

Figures 11a and b are sample plots of BRDF versus angle data. The plot title identifies the test sample, measurement wavelengths, and the test area on the sample when applicable. The horizontal and vertical scales are the same for all plots, 0 to 40 deg and 0.001 to 1 sr^{-1}, respectively. The broadband BRDF data (Fig. 11a) is presented on a single plot for each color tile. The legend identifies flown or unflown tile samples, and the left and right spot locations. Unflown left, unflown right, flown left, and flown right are abbreviated UNFL, UNFR, FL, and FR, respectively.

A sample plot of spectral BRDF data is presented in Fig. 11b. The 2.49-μm data were not presented in this plot (or the plots in the appendix) because the software limits the user to six curves per plot. The legend includes the center filter wavelength in μm.

REFERENCES

1. Nicodemus, F. E., "Directional Reflectance and Emissivity of an Opaque Surface." *Applied Optics*, Vol. 4, No. 7, July 1965, pp.767-773.

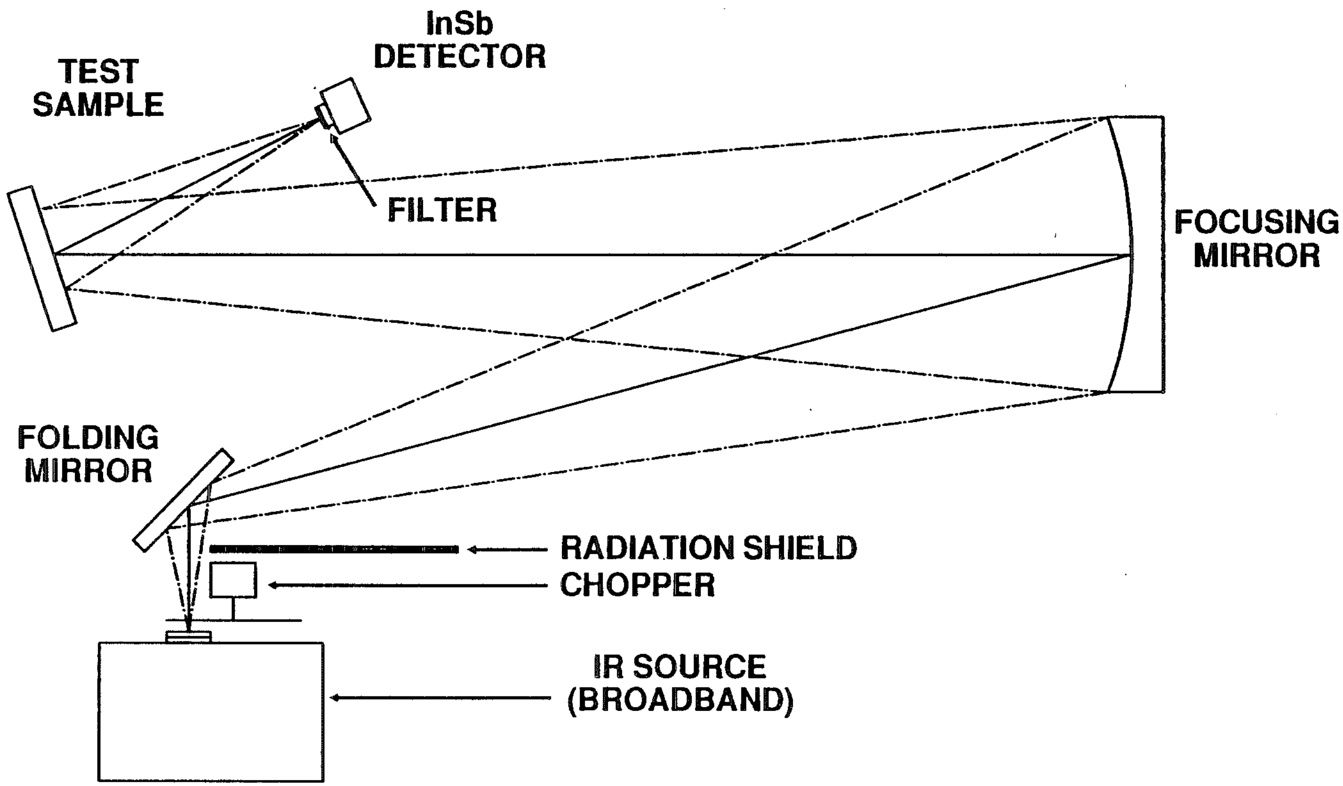
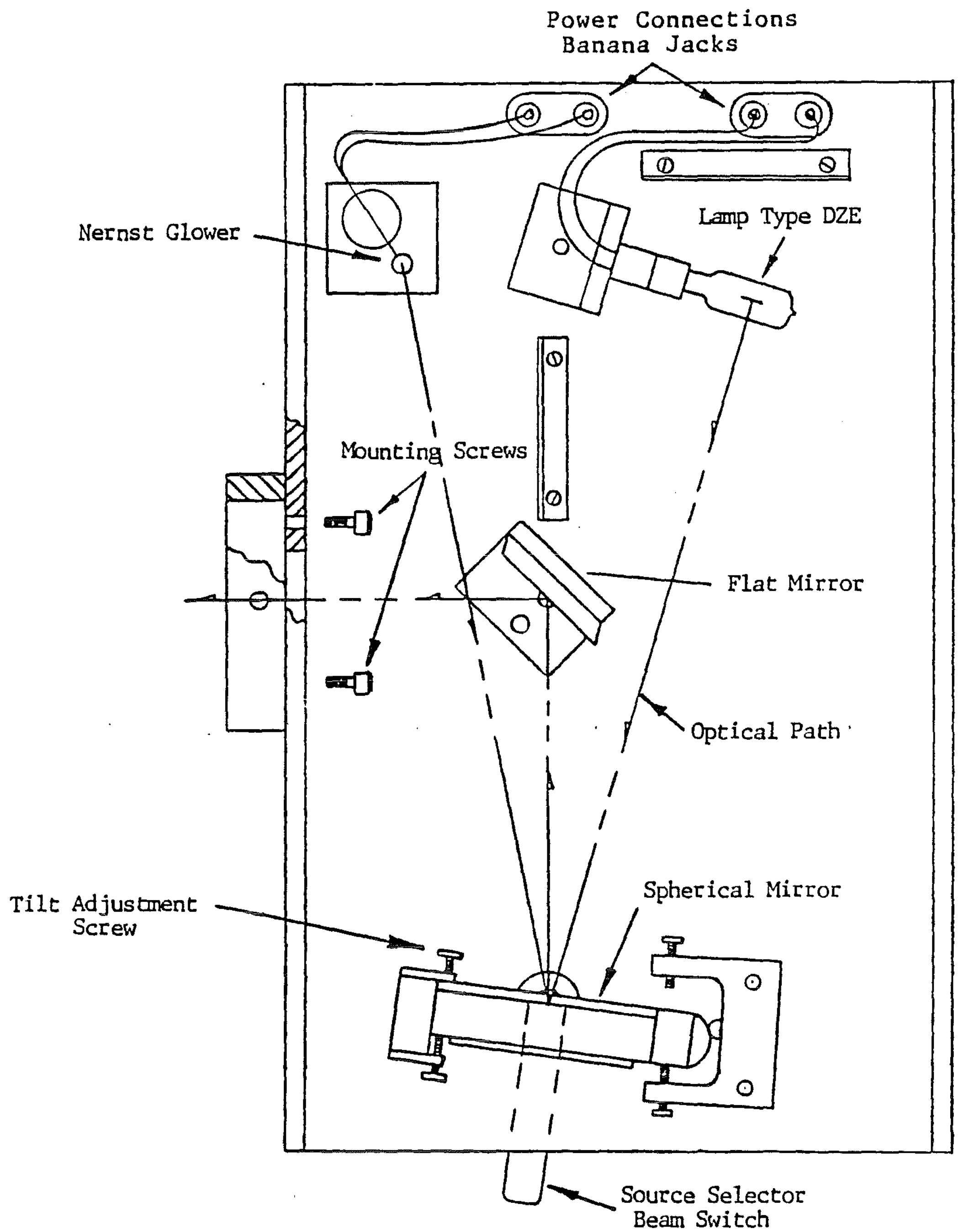


Figure 1. Diagram of BRDF Test Equipment



Note: Cooling Fan is Mounted Under Base Plate (Fan Not Shown)

740-20IR Source Module (Top View)
Optional Visible Source Shown

Figure 2. Diagram of Source Assembly

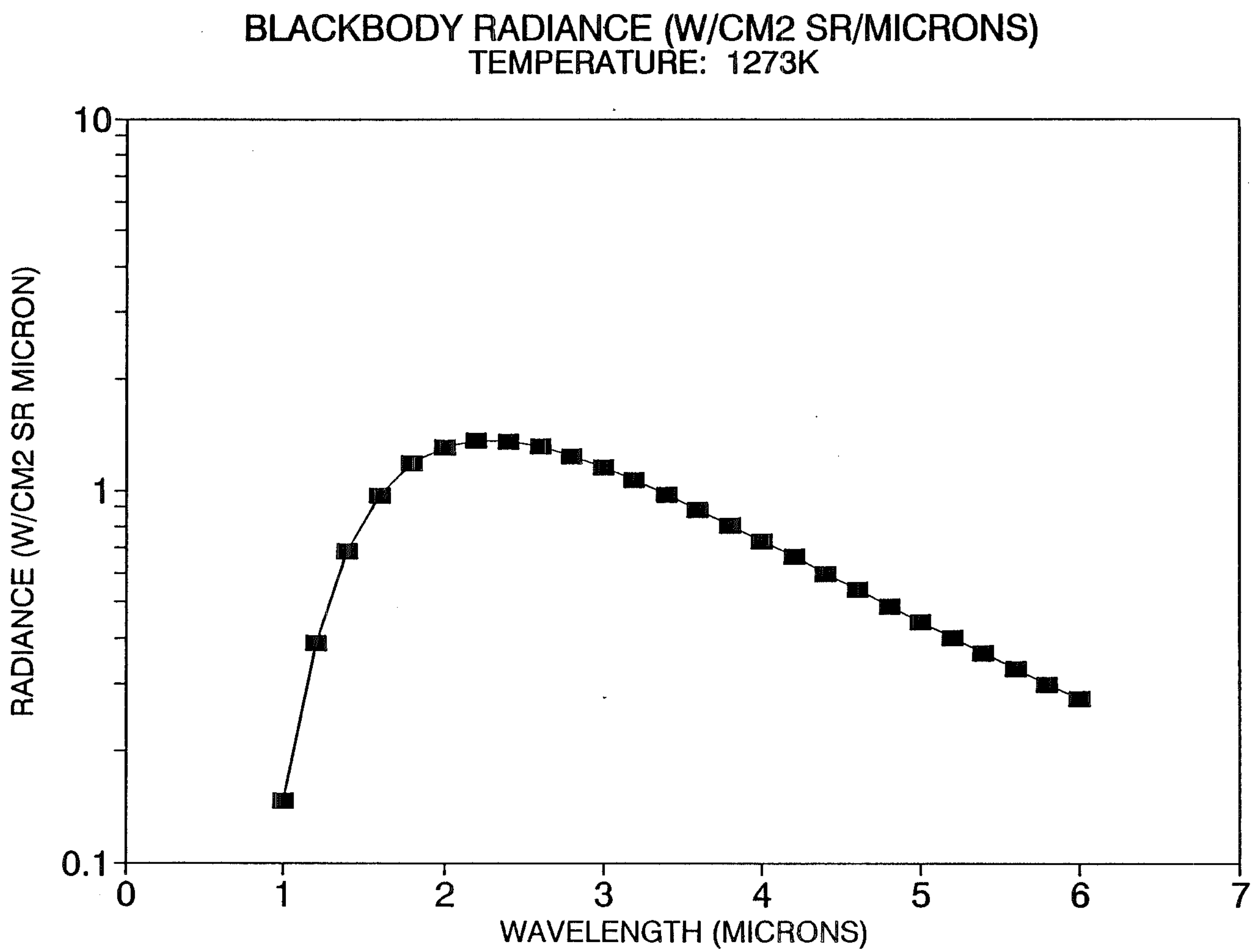


Figure 3. Blackbody Radiance

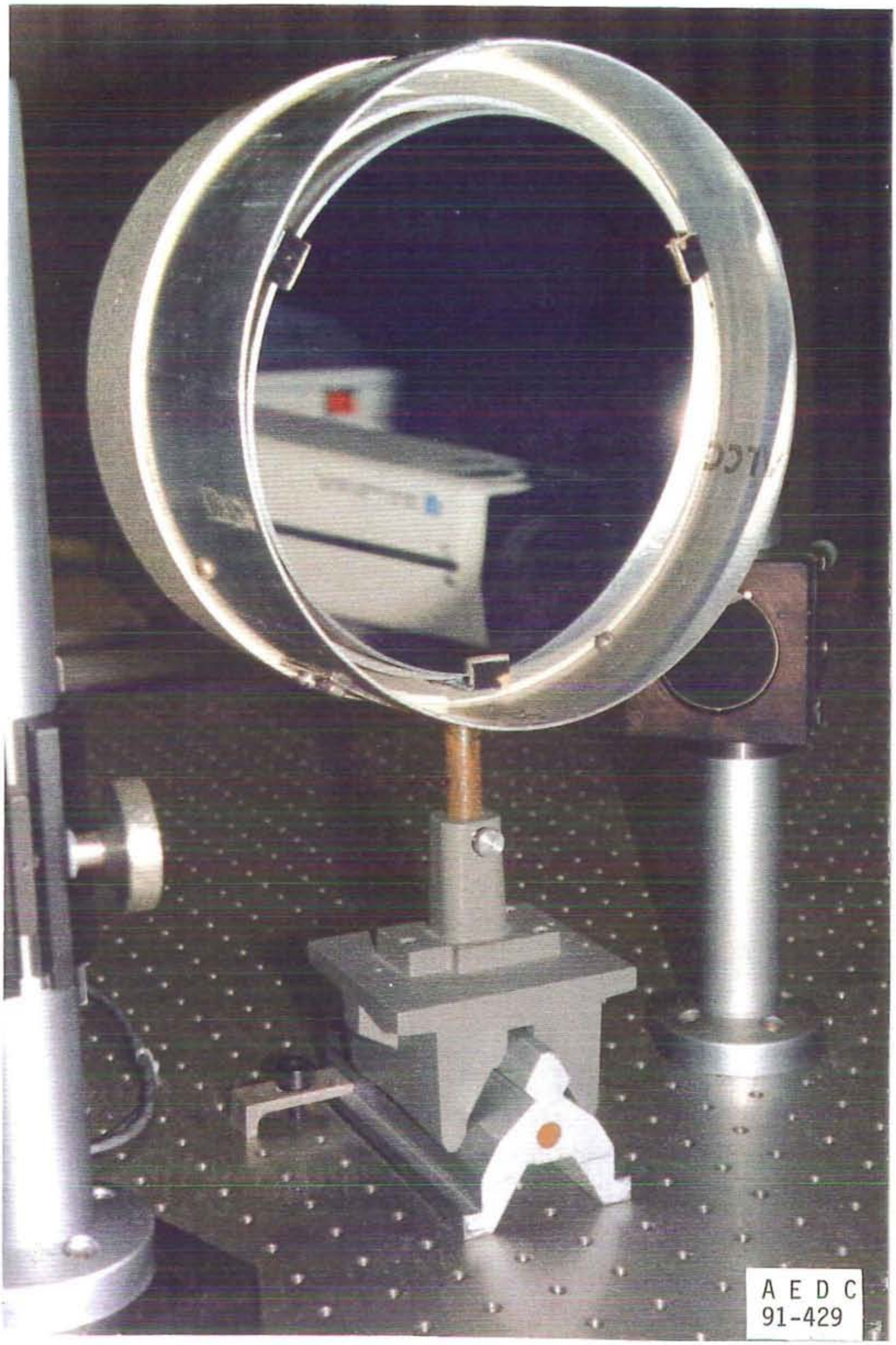


Figure 4. Source Re-imaging Mirror

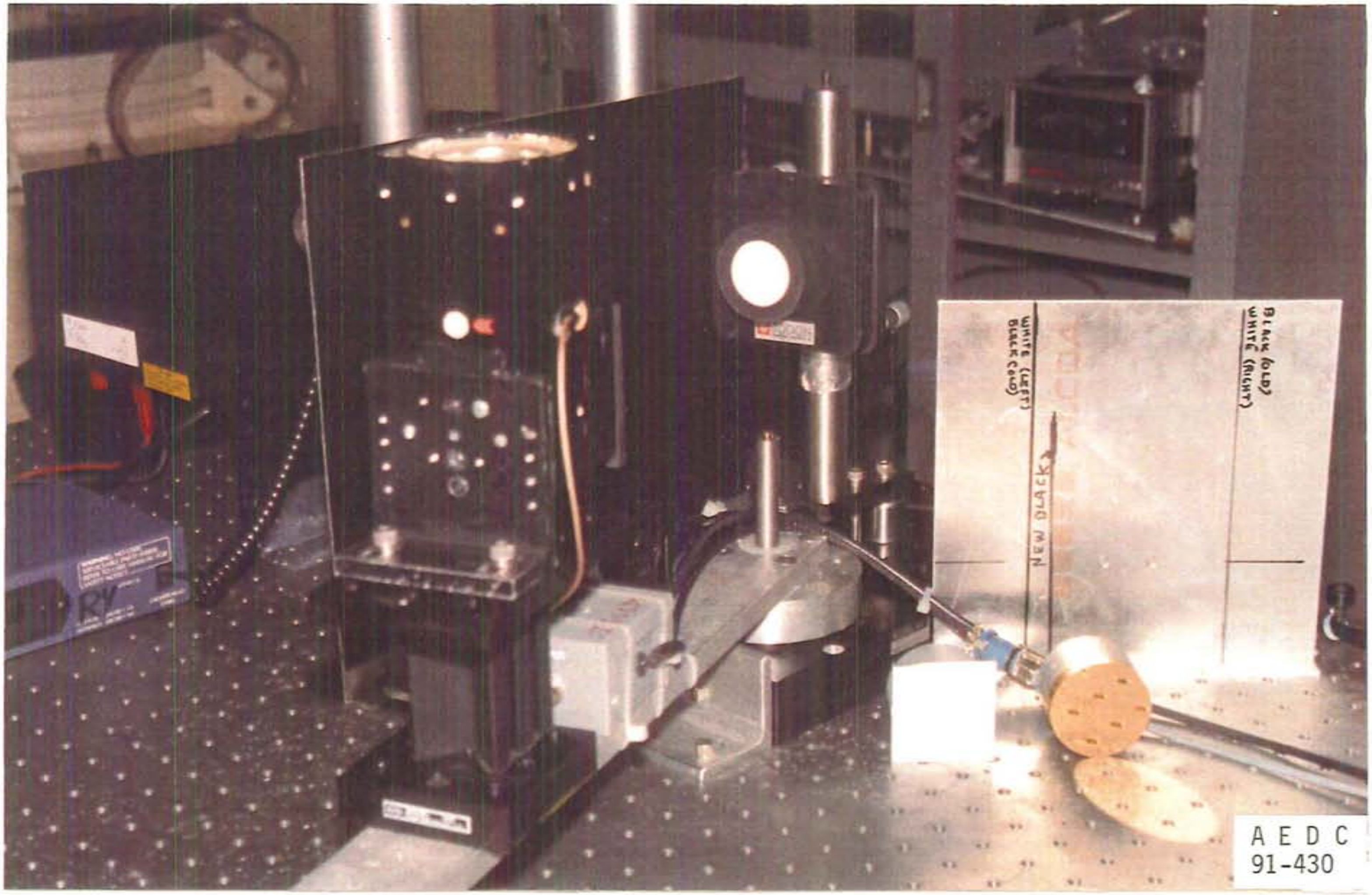


Figure 5. Test Sample Mounting Assembly

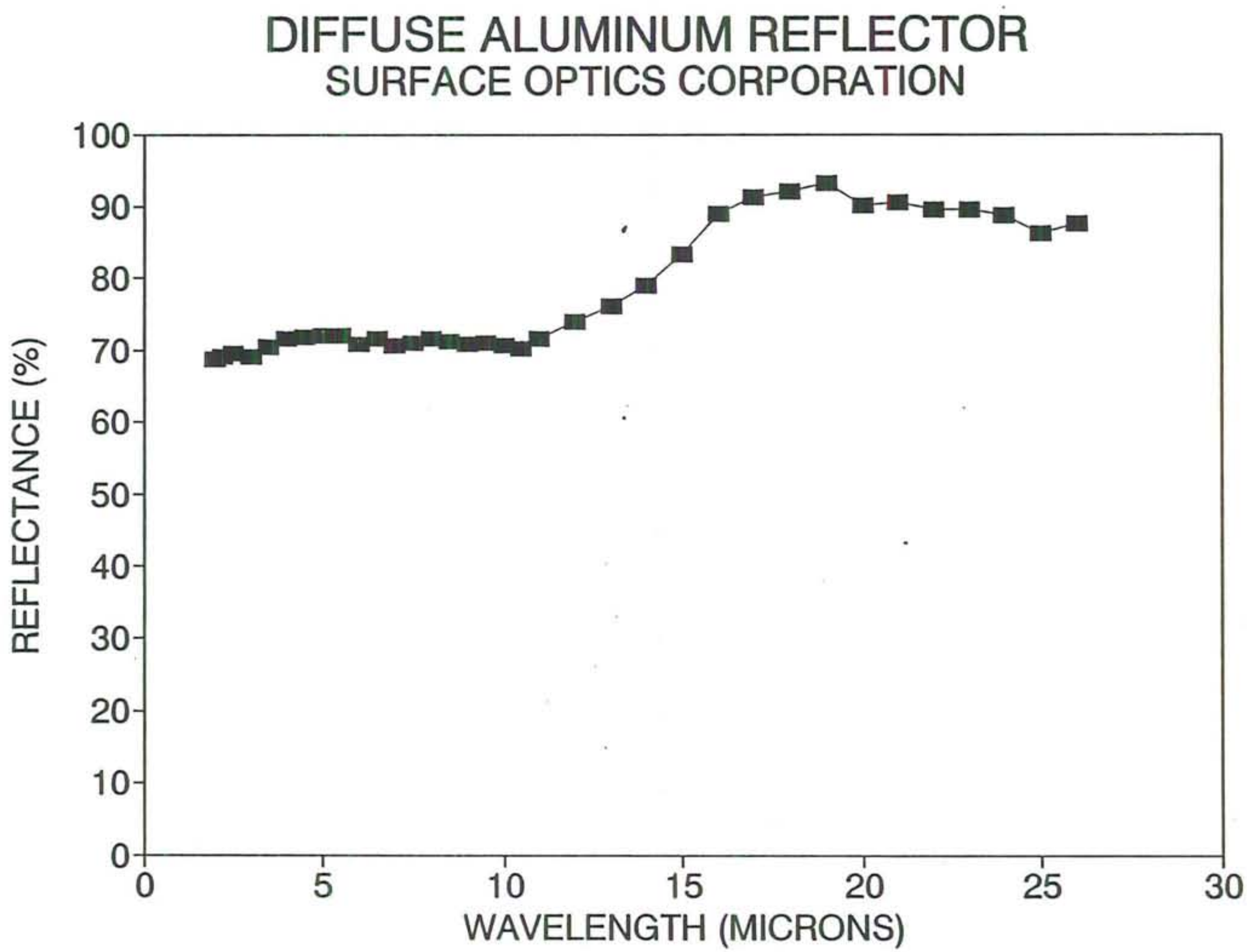


Figure 6. Aluminum Diffuser Spectral Reflectance

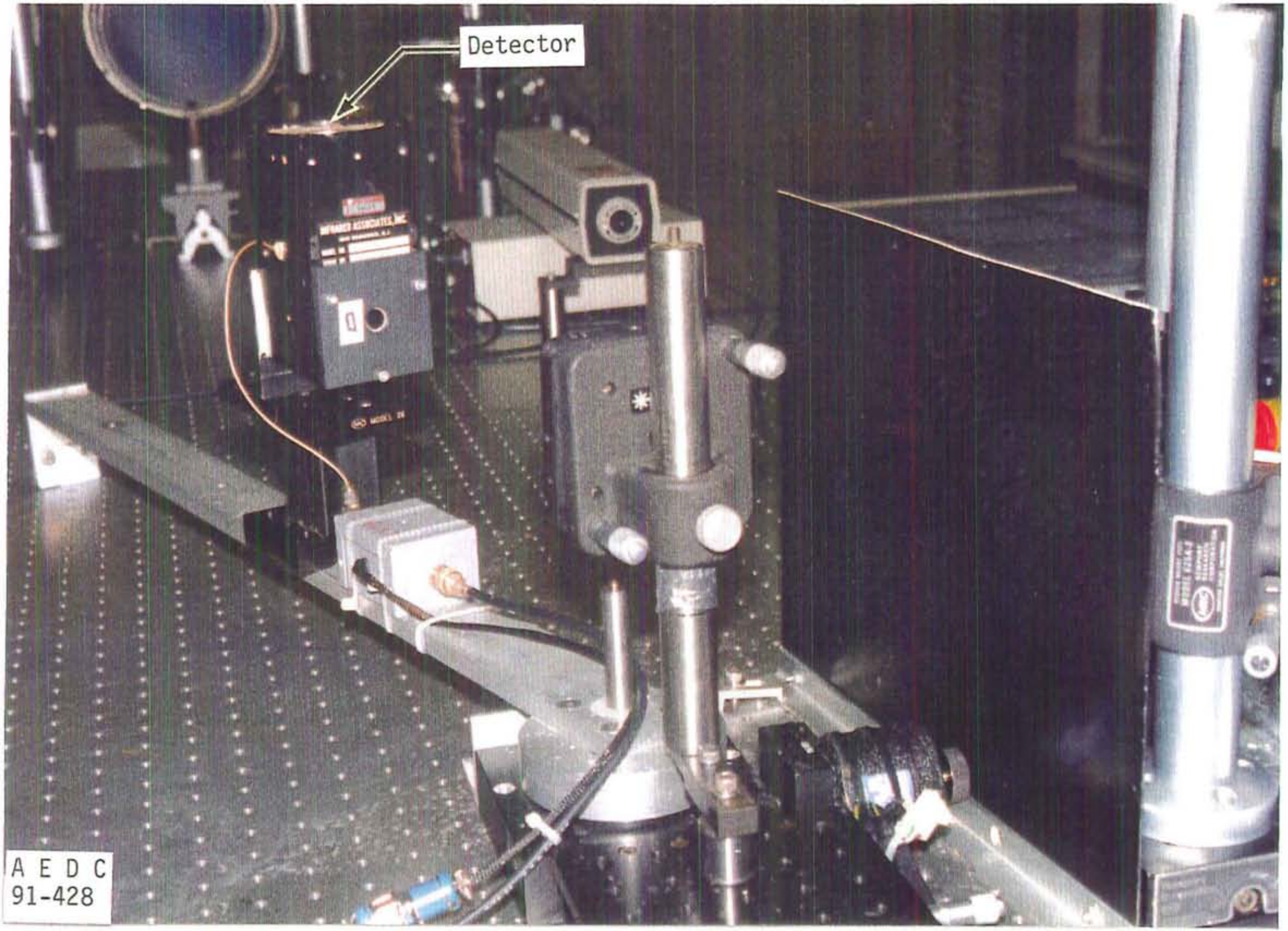


Figure 7. Detector Dewar Assembly

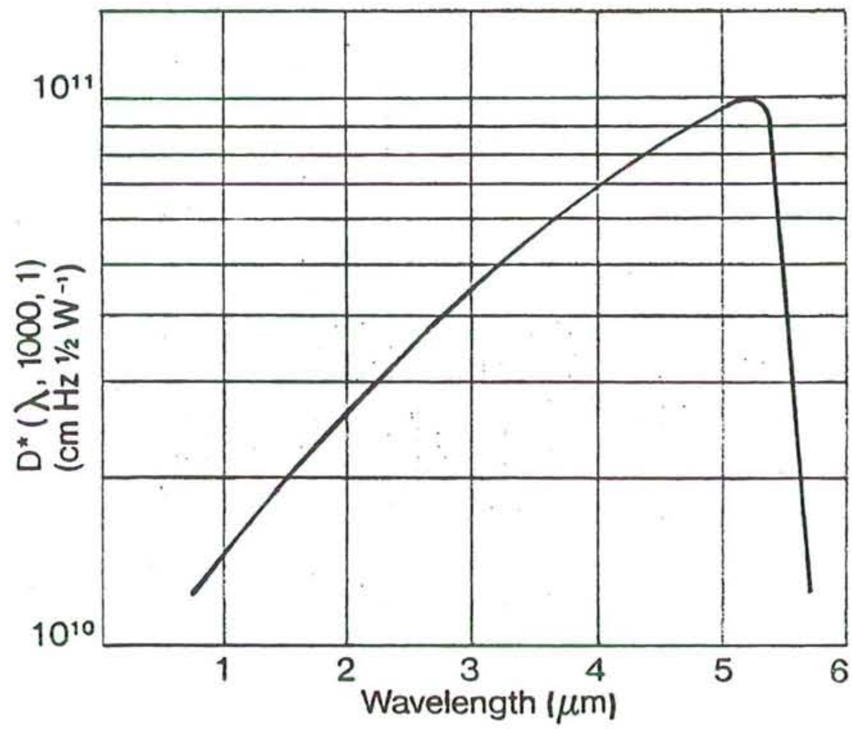


Figure 8. InSb Detector Spectral Detectivity

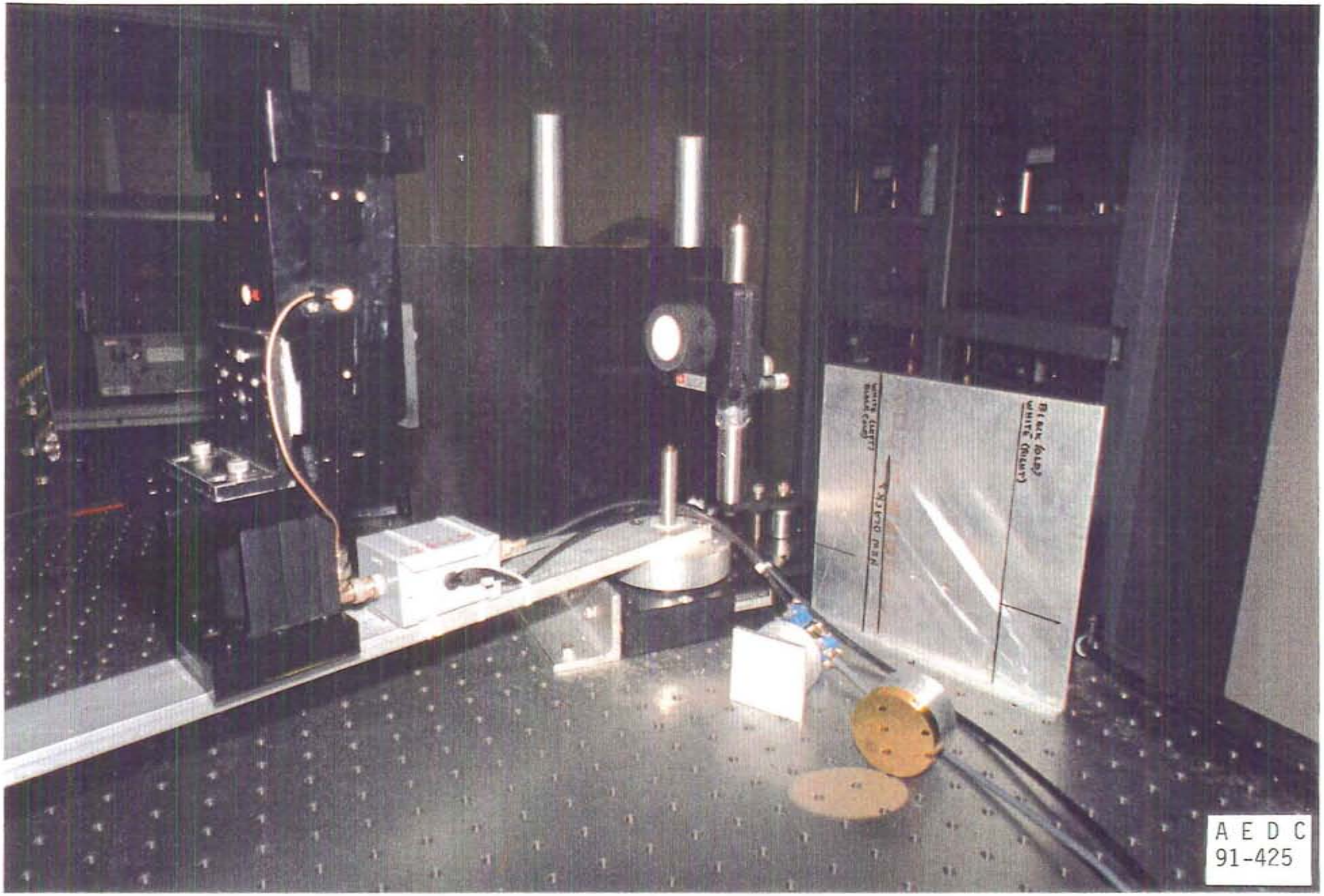
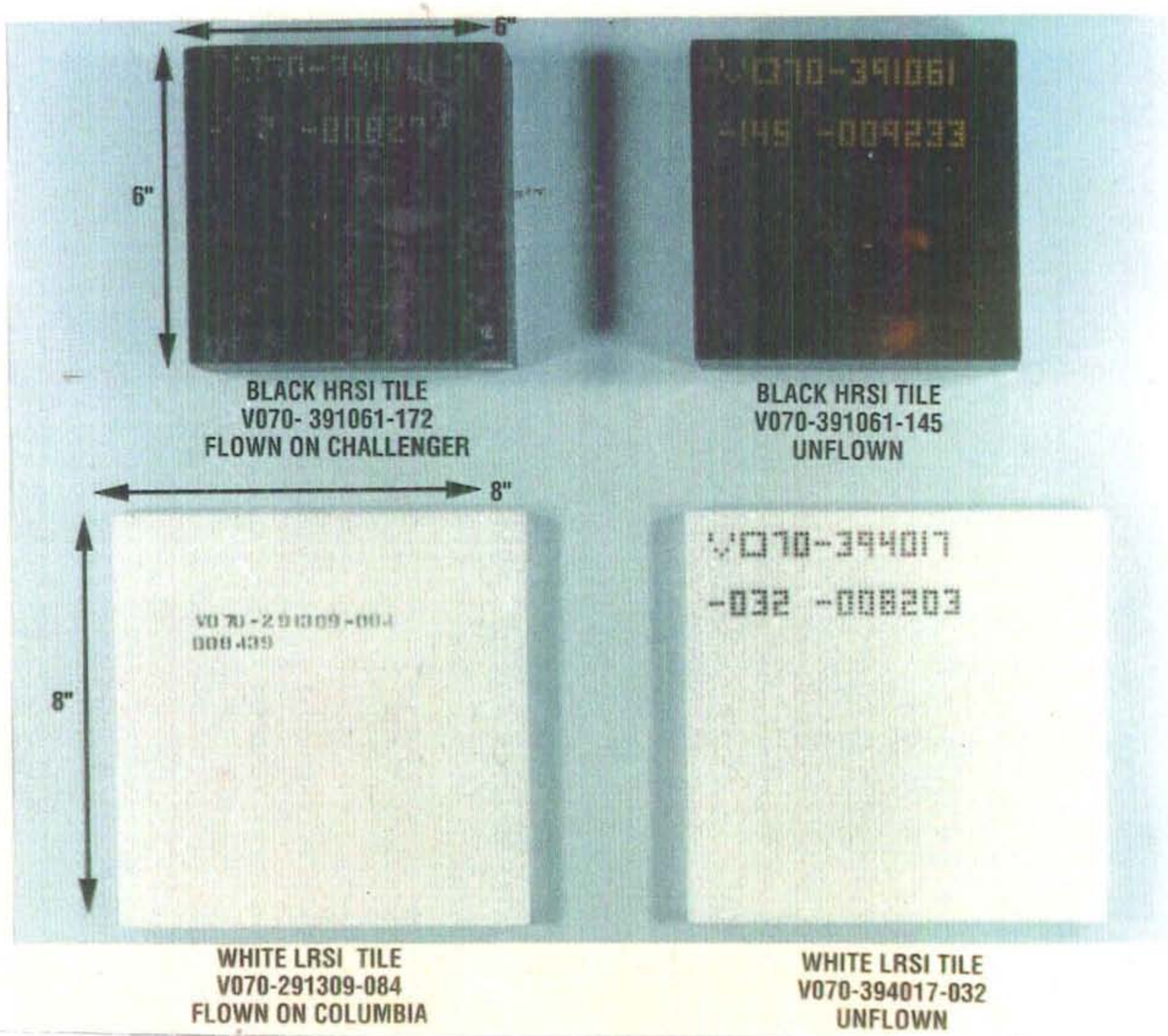
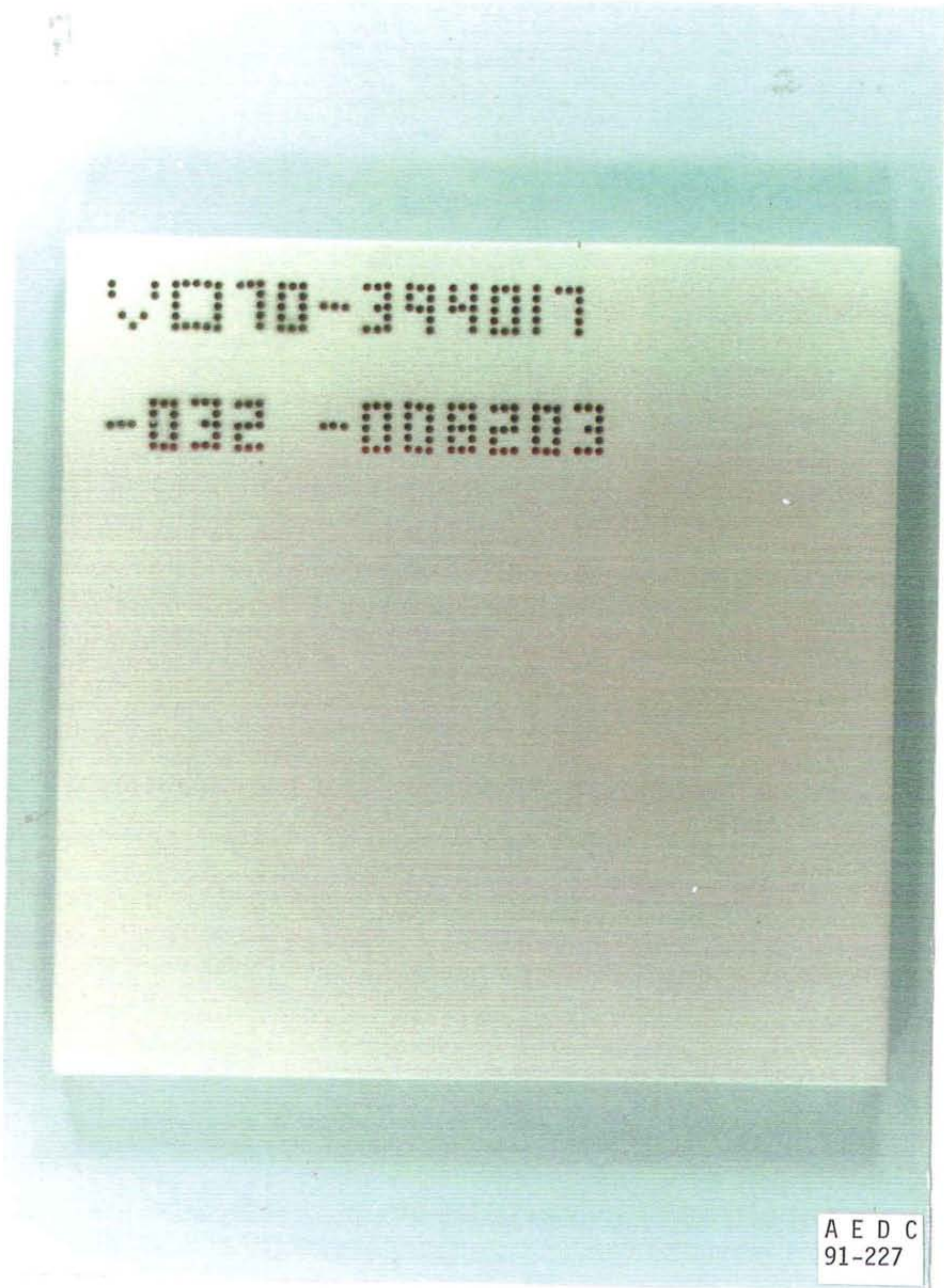


Figure 9. Rotary Arm Assembly



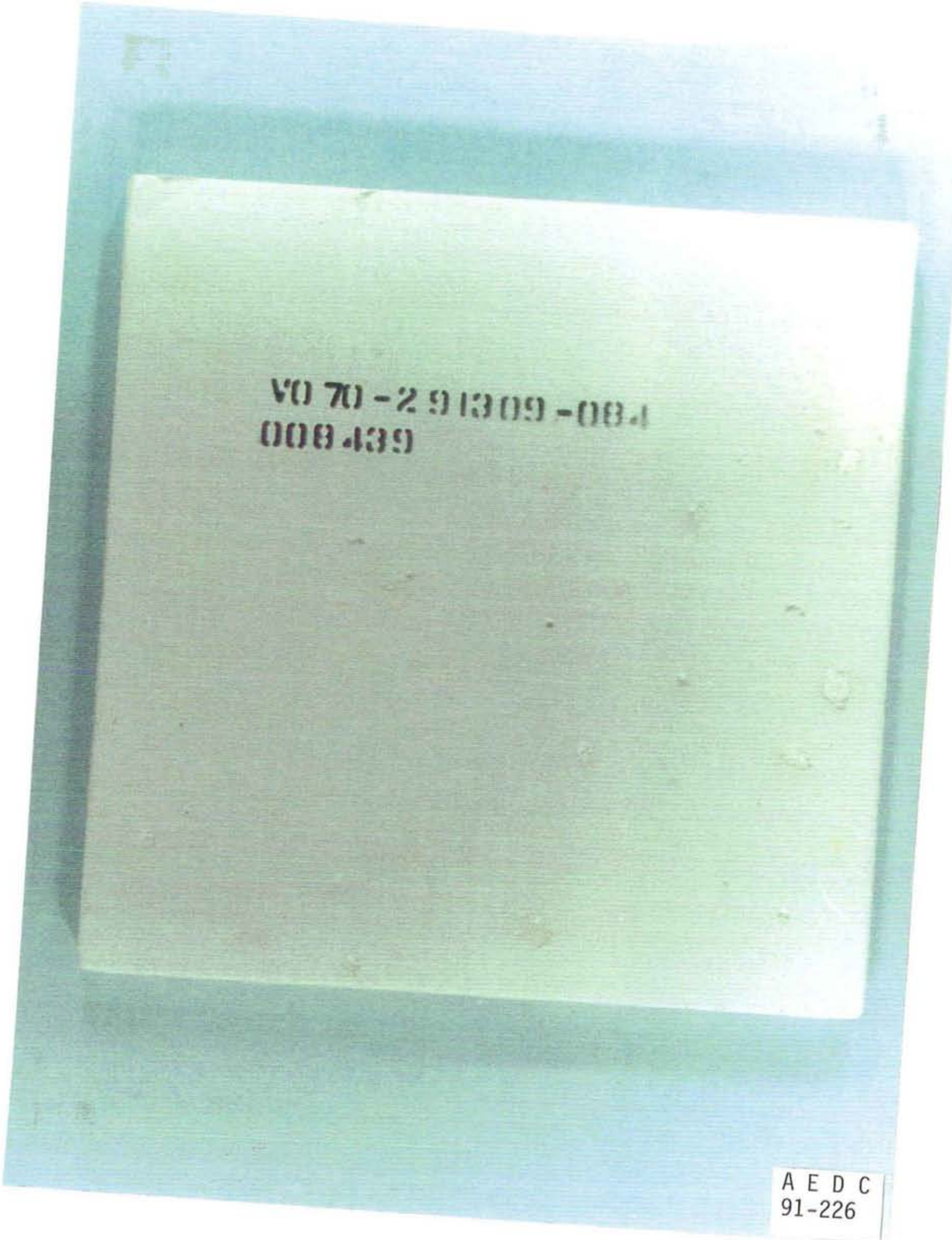
a. Tile Samples

Figure 10. Shuttle Tile Test Samples



b. White Unflown

Figure 10. Continued

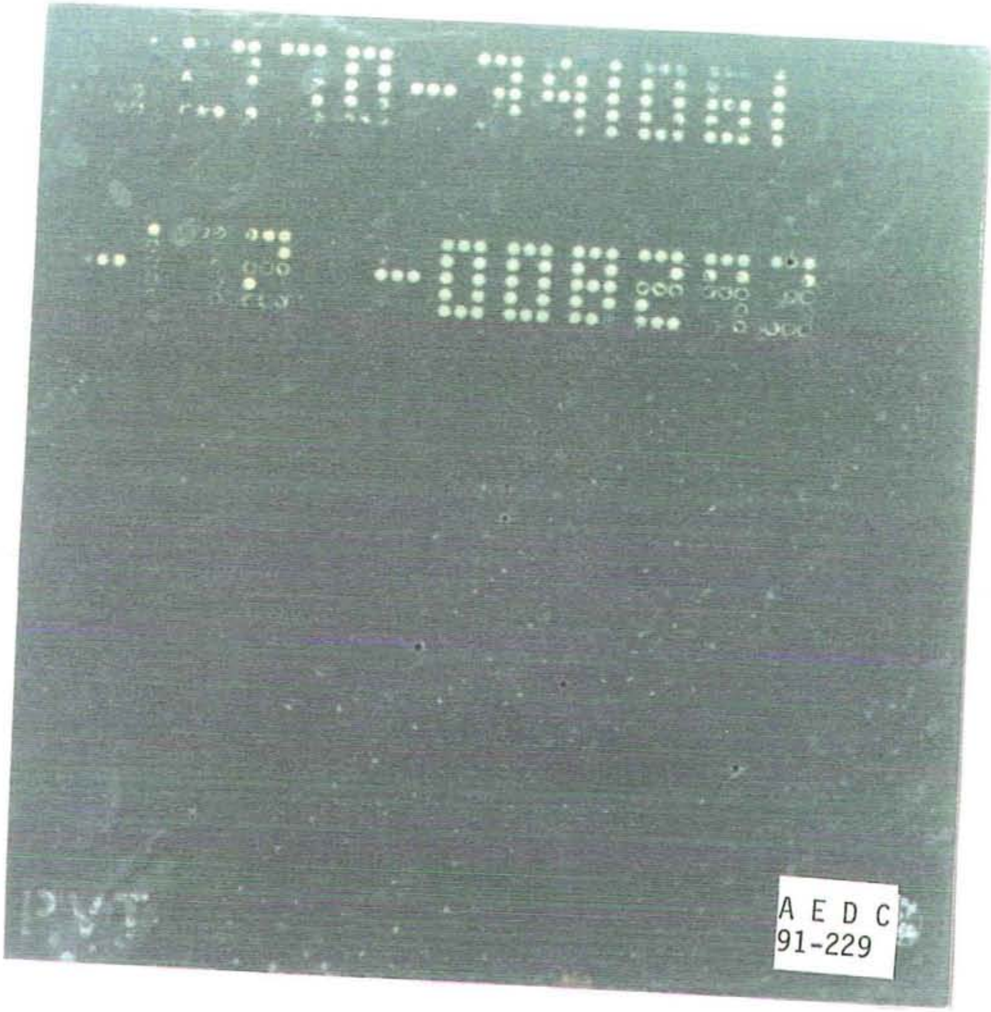


c. White Flown

Figure 10. Continued

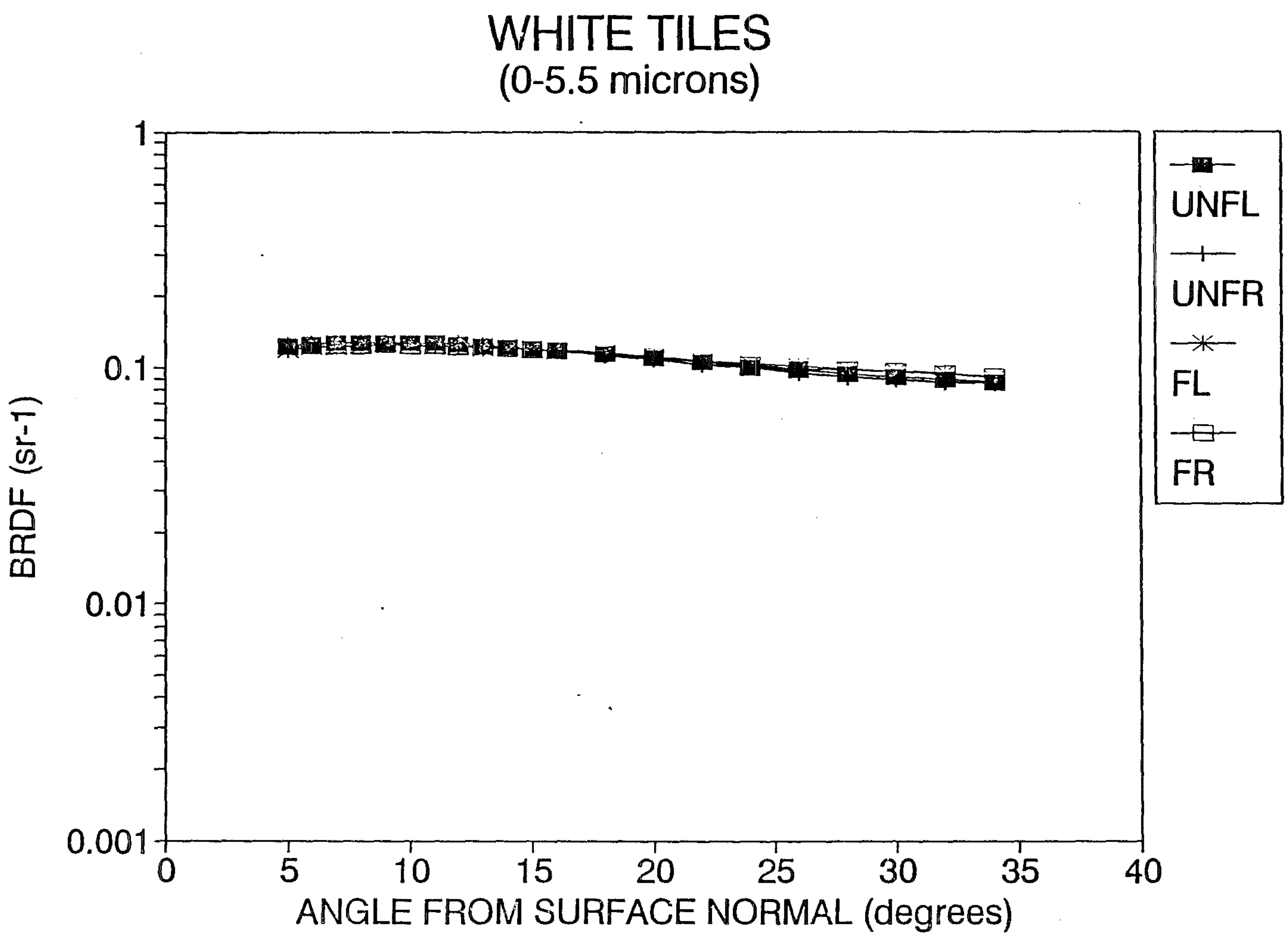
d. Black Unflown

Figure 10. Continued



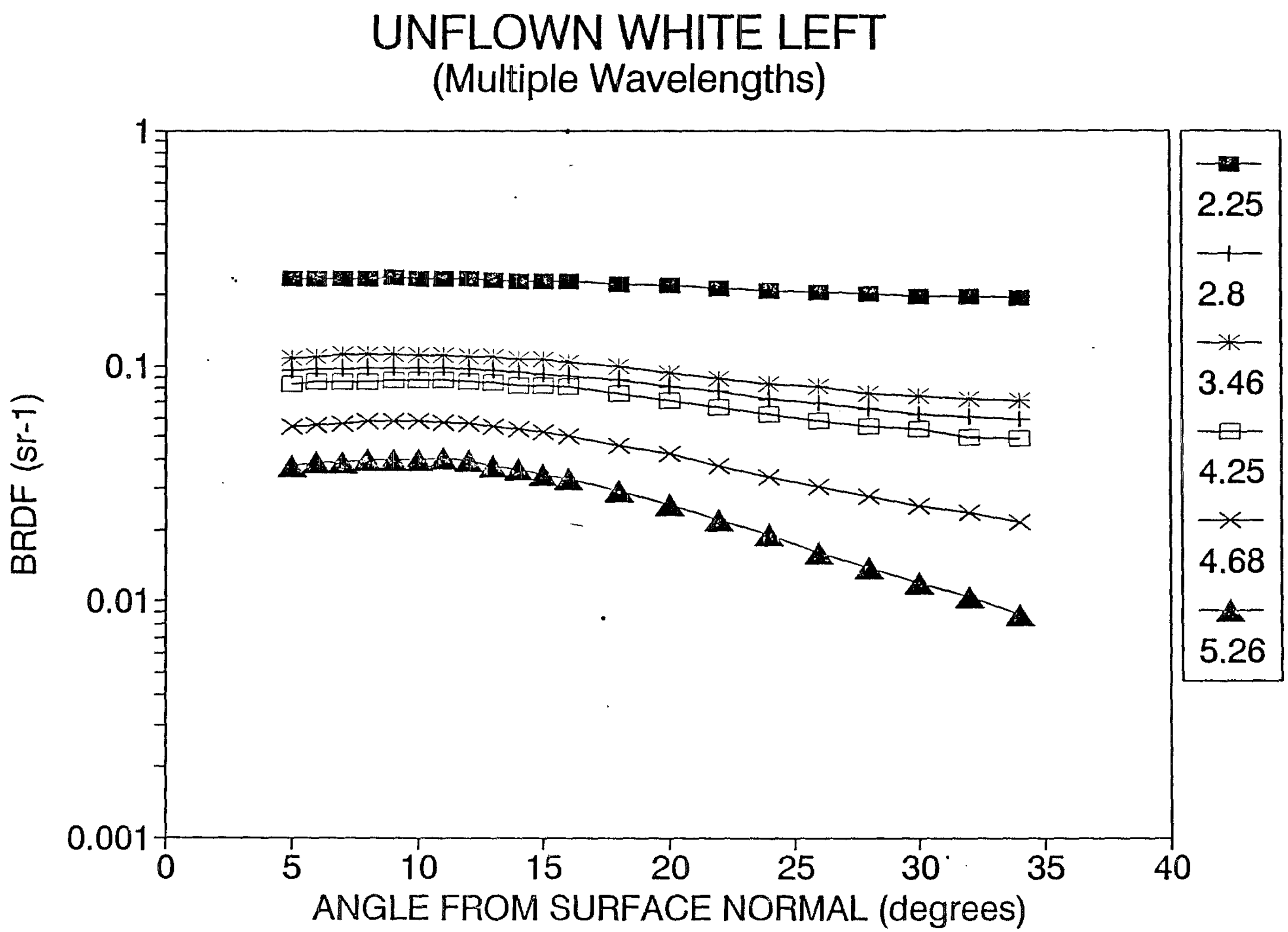
e. Black Flown

Figure 10. Concluded



a. Broadband Data

Figure 11. Sample Plots



b. Spectral Data

Figure 11. Concluded

TABLE 1

FILTER OPTICAL PROPERTIES

FILTER ID	WAVELENGTH (microns) L_1	L_2	L_c	DELTA L
4B8	2.05	2.49	2.27	0.44
4C1	2.45	2.52	2.49	0.07
4C8	2.70	2.91	2.81	0.21
6B2	3.42	3.50	3.46	0.08
6B1	4.14	4.35	4.25	0.21
6B5	4.56	4.79	4.68	0.23
8C2	5.09	5.43	5.26	0.34

TABLE 2

SAMPLE BRDF TABULATION

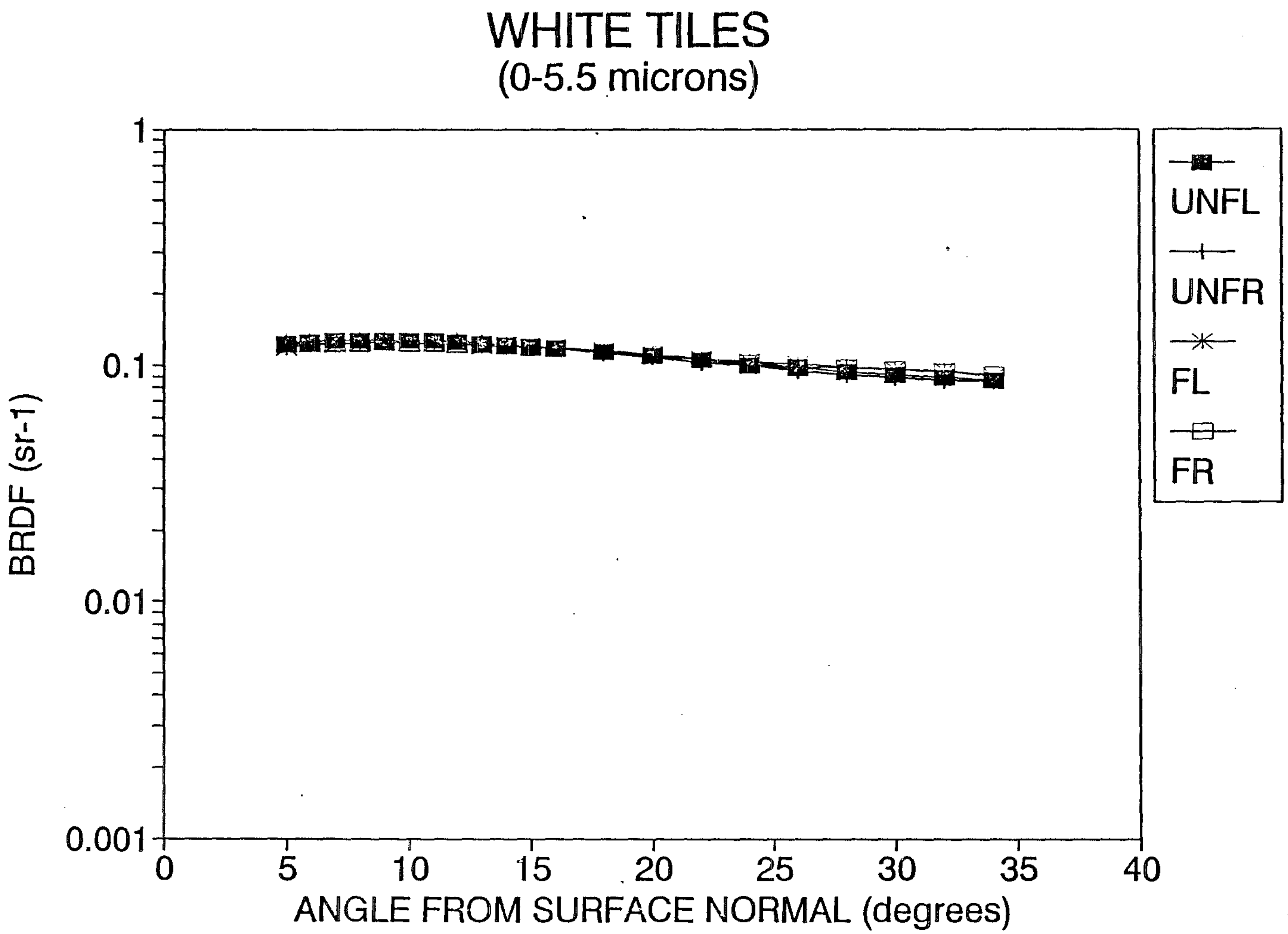
FILE: UNWHITEL.WQ1
SAMPLE: UNFLOWN WHITE LEFT
DIFFUSE STANDARD: ALUMINUM DIFFUSER
INCIDENCE ANGLE = 9 degrees
NOTE: ANGLE MEASURED FROM SURFACE NORMAL

ANGLE (DEG)	RUN 17 BB	RUN 27 2.27	RUN 37 2.49	RUN 47 2.81	RUN 57 3.46	RUN 67 4.25	RUN 77 4.68	RUN 87 5.26	RUN 97 BB
5	0.124	0.235	0.225	0.095	0.108	0.083	0.055	0.037	0.122
6	0.126	0.236	0.226	0.097	0.110	0.086	0.056	0.039	0.124
7	0.127	0.237	0.227	0.098	0.112	0.086	0.057	0.039	0.125
8	0.127	0.237	0.229	0.098	0.113	0.086	0.058	0.040	0.126
9	0.127	0.237	0.229	0.098	0.112	0.087	0.058	0.040	0.126
10	0.127	0.237	0.228	0.099	0.112	0.087	0.058	0.040	0.126
11	0.126	0.236	0.228	0.098	0.111	0.087	0.058	0.040	0.125
12	0.126	0.235	0.227	0.097	0.110	0.087	0.057	0.039	0.124
13	0.124	0.233	0.225	0.096	0.110	0.085	0.055	0.038	0.123
14	0.122	0.231	0.223	0.095	0.107	0.083	0.054	0.036	0.121
15	0.121	0.230	0.222	0.093	0.106	0.082	0.052	0.035	0.119
16	0.118	0.228	0.220	0.091	0.104	0.081	0.050	0.033	0.117
18	0.114	0.224	0.215	0.087	0.100	0.076	0.046	0.029	0.113
20	0.110	0.219	0.211	0.082	0.094	0.071	0.042	0.026	0.109
22	0.105	0.215	0.205	0.078	0.088	0.066	0.038	0.022	0.105
24	0.100	0.210	0.201	0.073	0.084	0.063	0.034	0.019	0.100
26	0.097	0.206	0.197	0.069	0.081	0.058	0.031	0.016	0.097
28	0.094	0.203	0.193	0.066	0.076	0.055	0.028	0.014	0.094
30	0.091	0.199	0.191	0.063	0.074	0.054	0.025	0.012	0.091
32	0.088	0.197	0.188	0.061	0.072	0.050	0.024	0.010	0.089
34	0.086	0.195	0.186	0.059	0.071	0.049	0.022	0.009	0.087

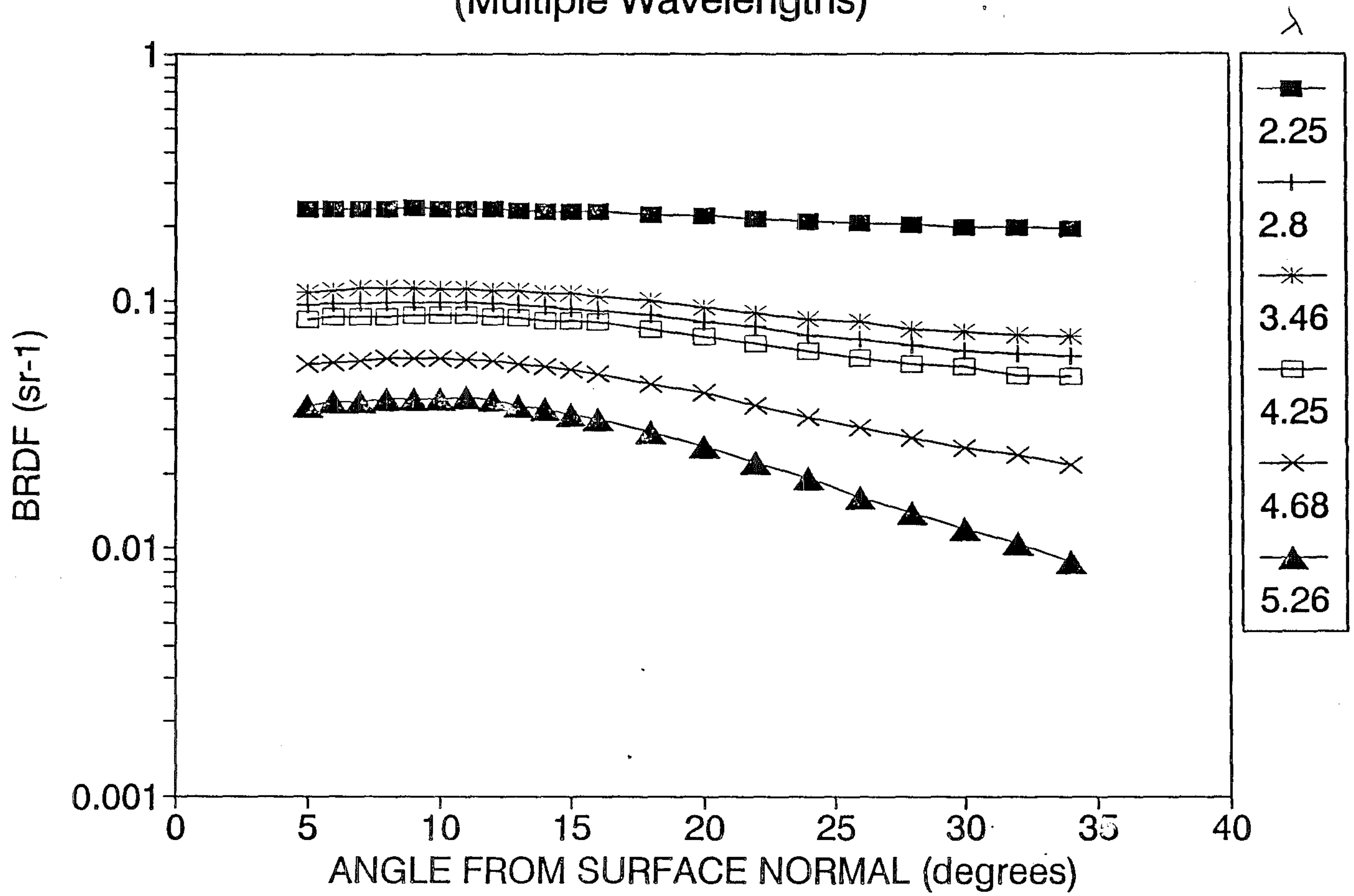
APPENDIX

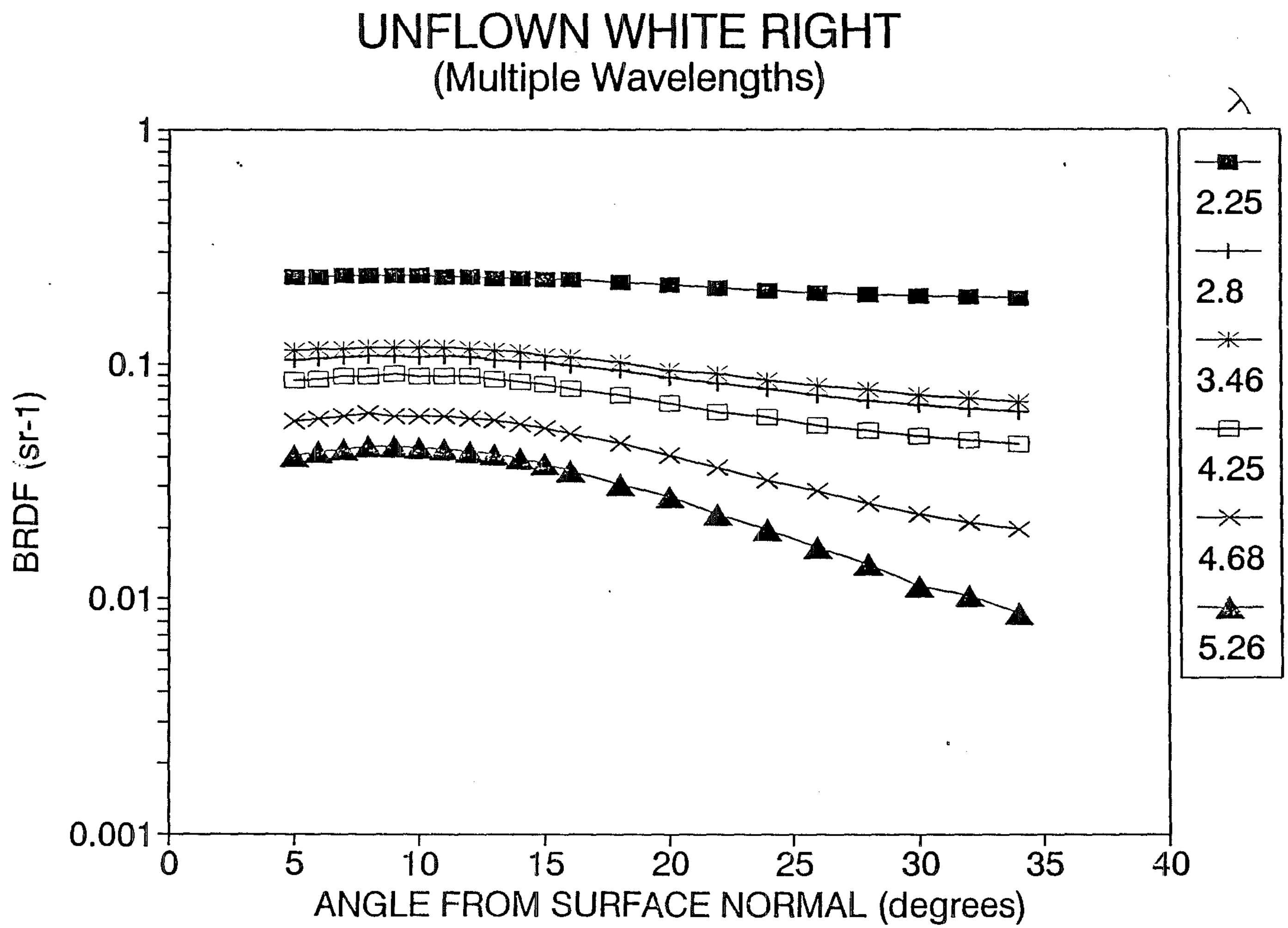
DATA PACKAGE CONTENTS

SAMPLE DESCRIPTION	TABLE/PLOT	POSITION	WAVELENGTH
WHITE, BOTH	PLOT	BOTH	BROADBAND
WHITE, UNFLOWN	PLOT	LEFT	MULTIPLE
WHITE, UNFLOWN	PLOT	RIGHT	MULTIPLE
WHITE, FLOWN	PLOT	LEFT	MULTIPLE
WHITE, FLOWN	PLOT	RIGHT	MULTIPLE
BLACK, BOTH	PLOT	BOTH	BROADBAND
BLACK, UNFLOWN	PLOT	LEFT	MULTIPLE
BLACK, FLOWN	PLOT	LEFT	MULTIPLE
BLACK, FLOWN	PLOT	RIGHT	MULTIPLE
WHITE, UNFLOWN	TABLE	LEFT	MULTIPLE
WHITE, UNFLOWN	TABLE	RIGHT	MULTIPLE
WHITE, FLOWN	TABLE	LEFT	MULTIPLE
WHITE, FLOWN	TABLE	RIGHT	MULTIPLE
BLACK, UNFLOWN	TABLE	LEFT	MULTIPLE
BLACK, FLOWN	TABLE	LEFT	MULTIPLE
BLACK, FLOWN	TABLE	RIGHT	MULTIPLE

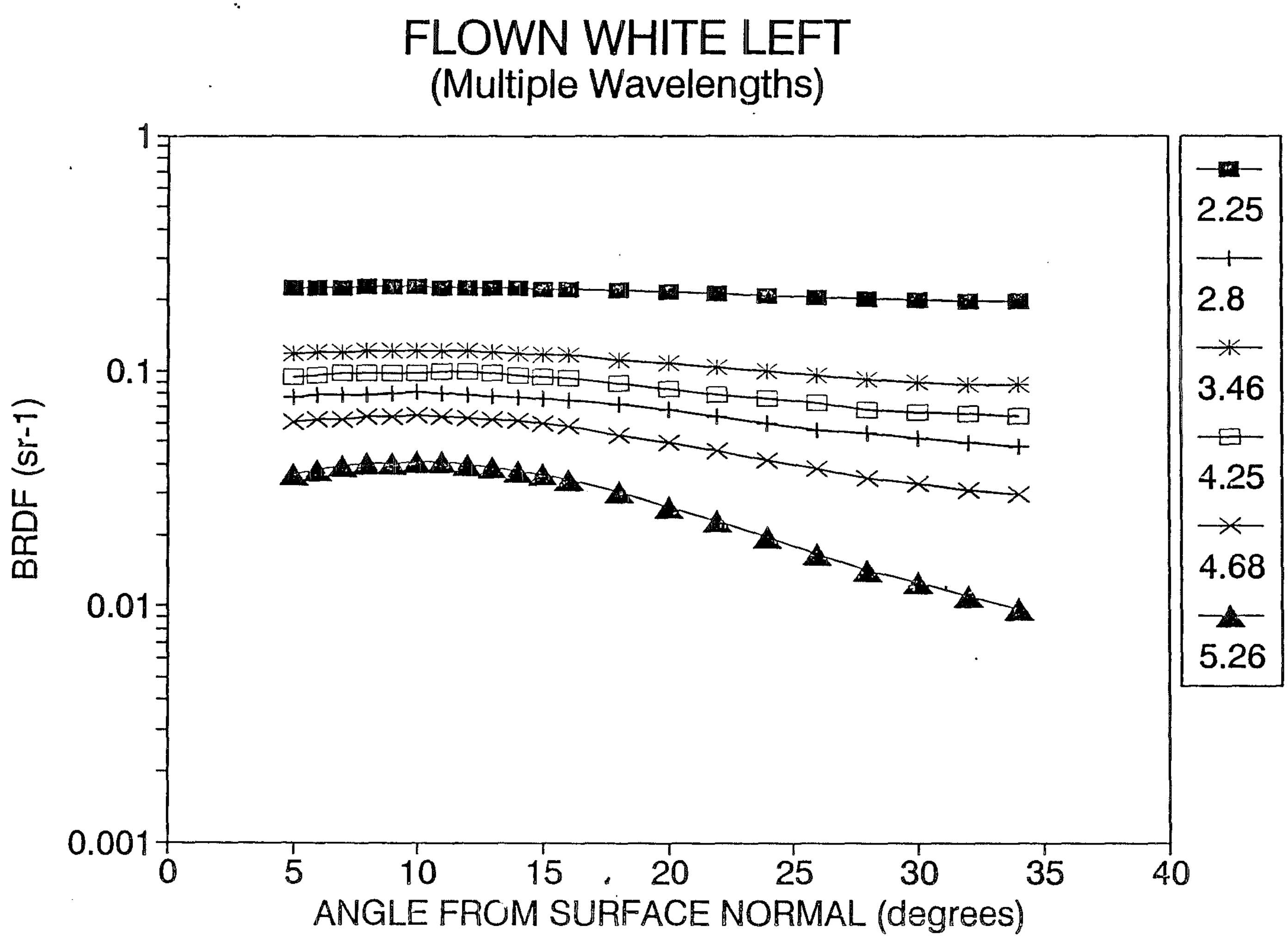

WHITE TILES
(0-5.5 microns)
BRDF (sr-1)
1
0.1
0.01
0.001
0
5
10
15
20
25
30
35
40
ANGLE FROM SURFACE NORMAL (degrees)
UNFL
UNFR
FL
FR

UNFLOWN WHITE LEFT
(Multiple Wavelengths)

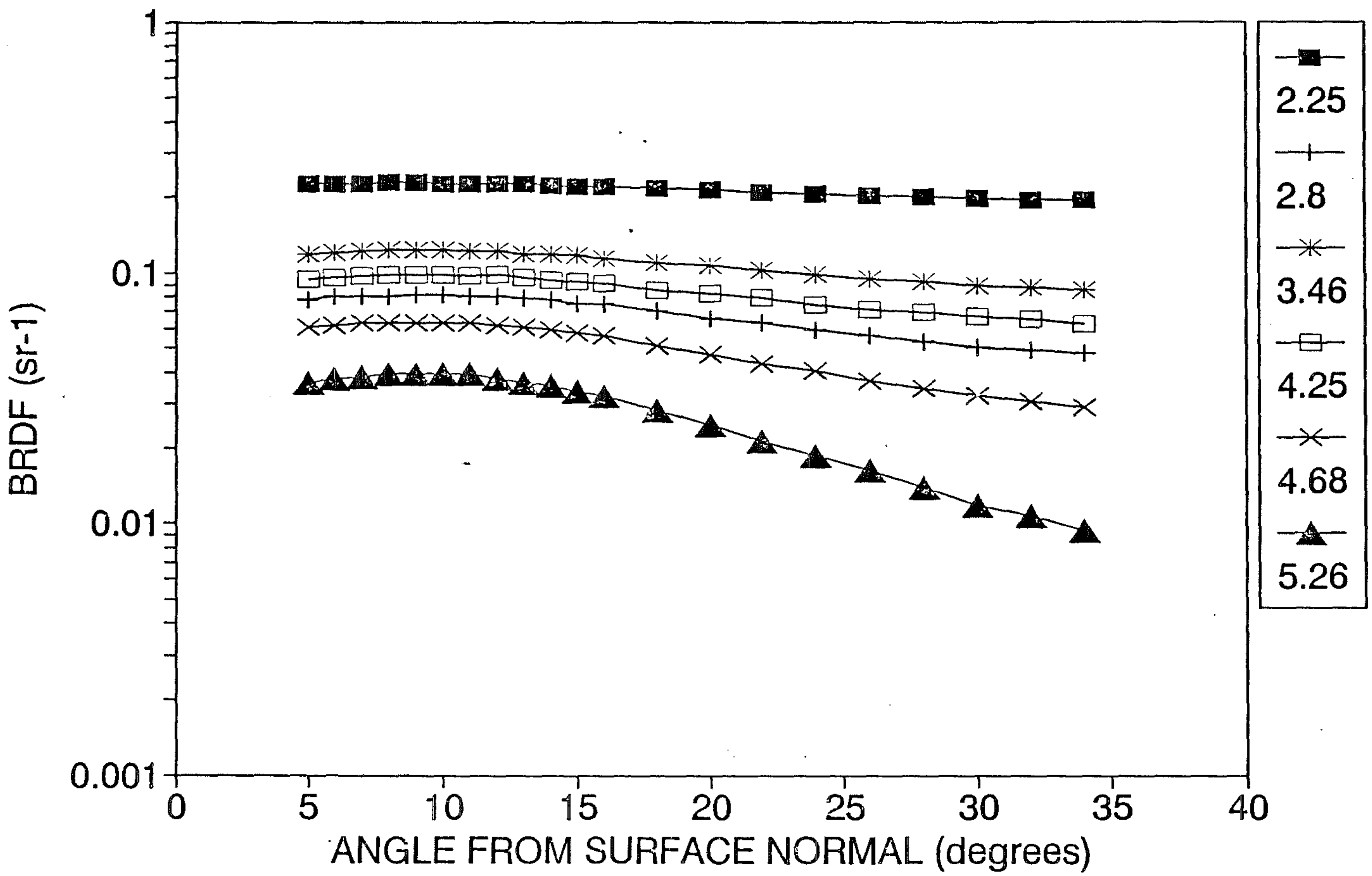


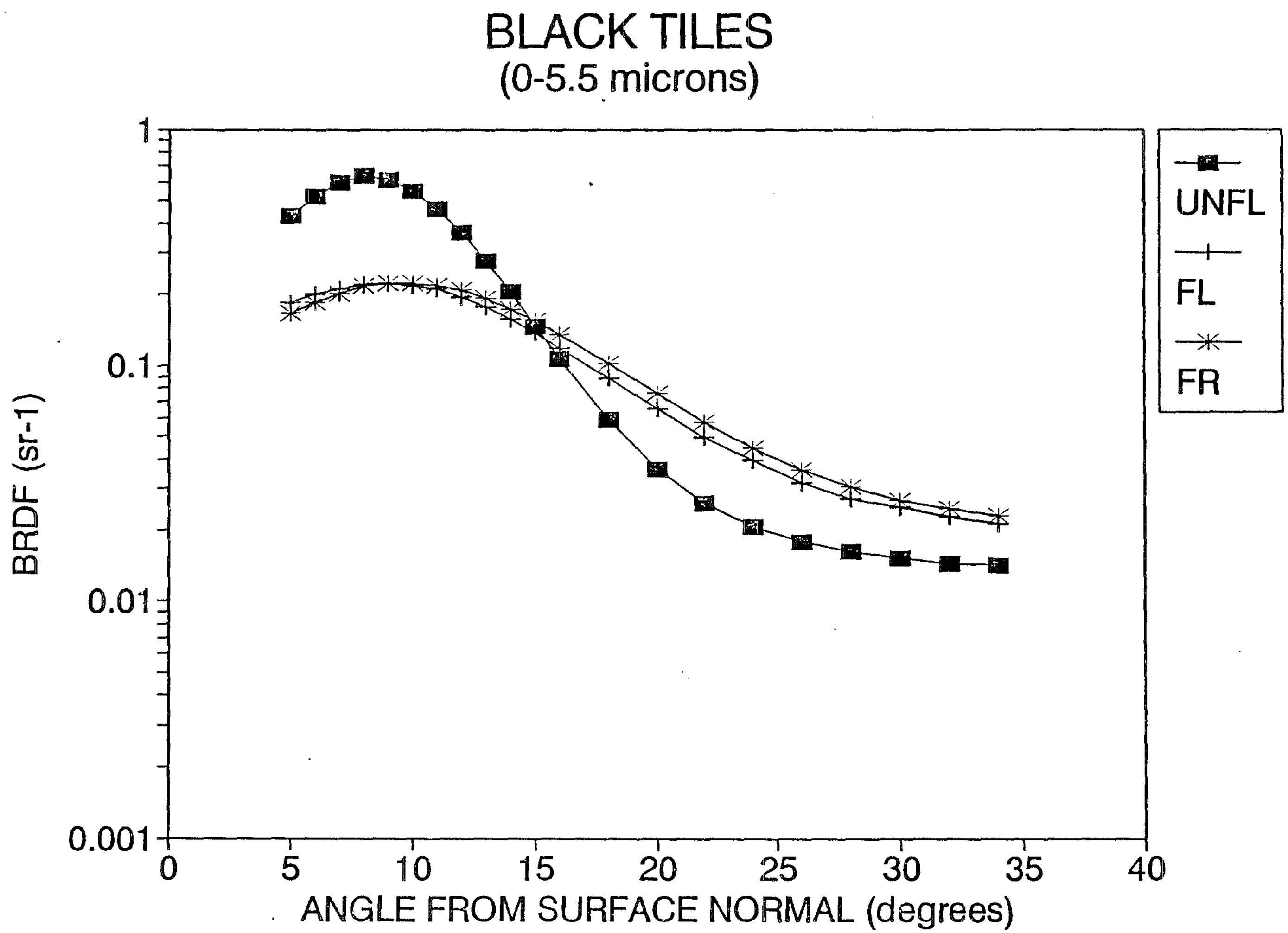


UNFLOWN WHITE RIGHT
(Multiple Wavelengths)
BRDF (sr-1)
1
0.1
0.01
0.001
0
5
10
15
20
25
30
35
40
ANGLE FROM SURFACE NORMAL (degrees)
λ
2.25
2.8
3.46
4.25
4.68
5.26

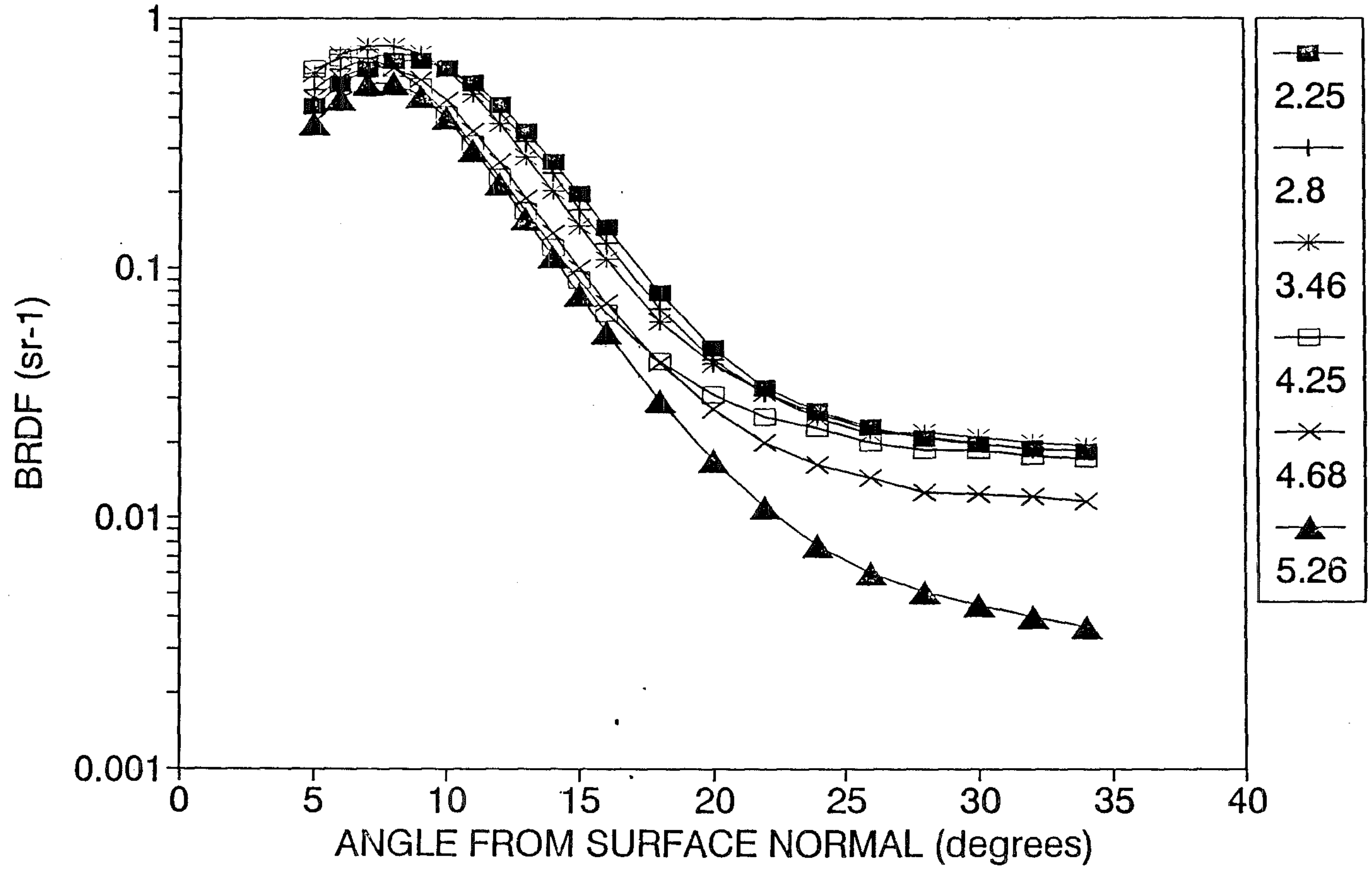

FLOWN WHITE LEFT
(Multiple Wavelengths)
BRDF (sr-1)
1
0.1
0.01
0.001
0
5
10
15
20
25
30
35
40
ANGLE FROM SURFACE NORMAL (degrees)
2.25
2.8
3.46
4.25
4.68
5.26

FLOWN WHITE RIGHT
(Multiple Wavelengths)

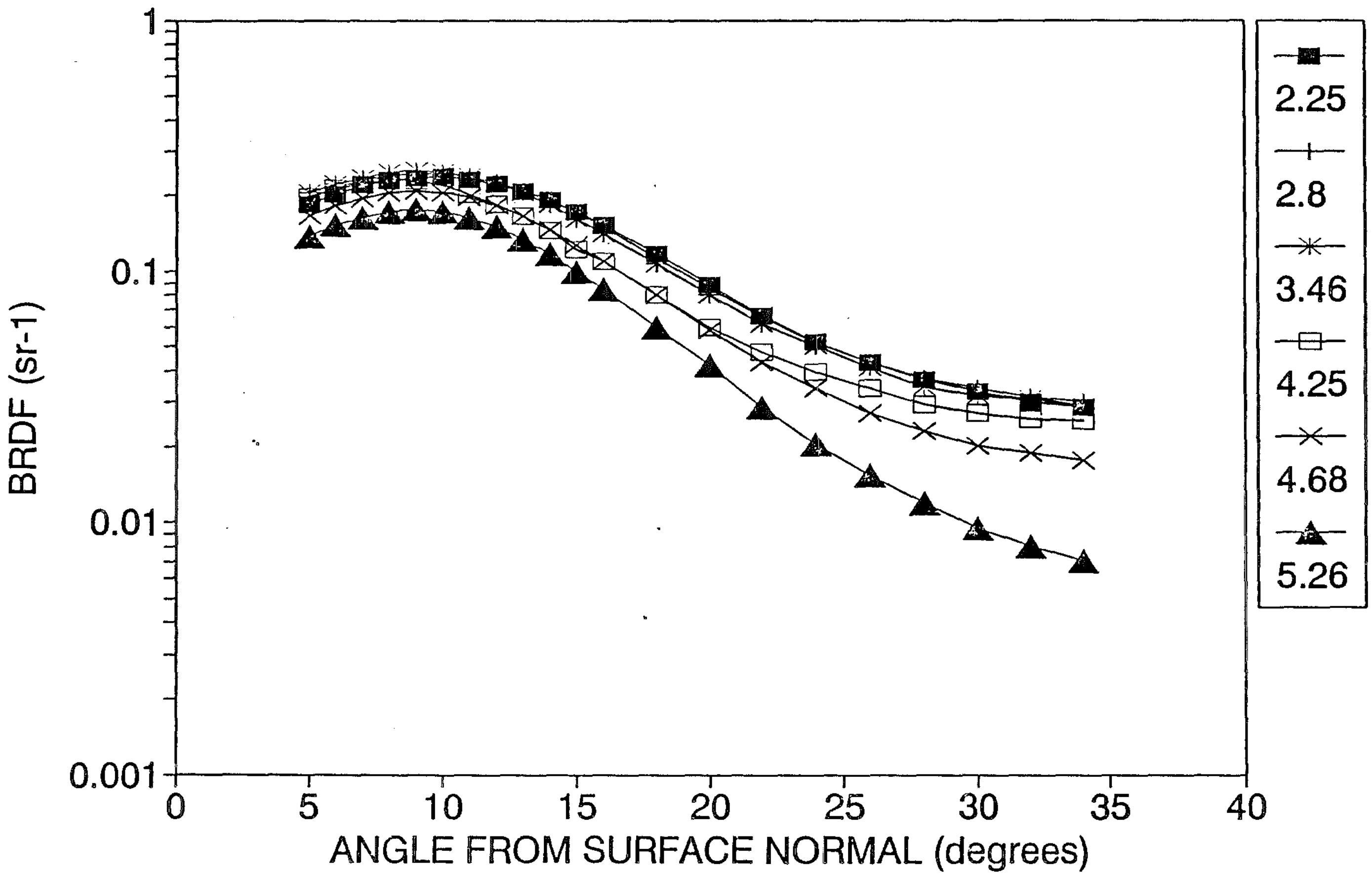



BLACK TILES
(0-5.5 microns)
BRDF (sr-1)
1
0.1
0.01
0.001
0
5
10
15
20
25
30
35
40
ANGLE FROM SURFACE NORMAL (degrees)
UNFL
FL
FR

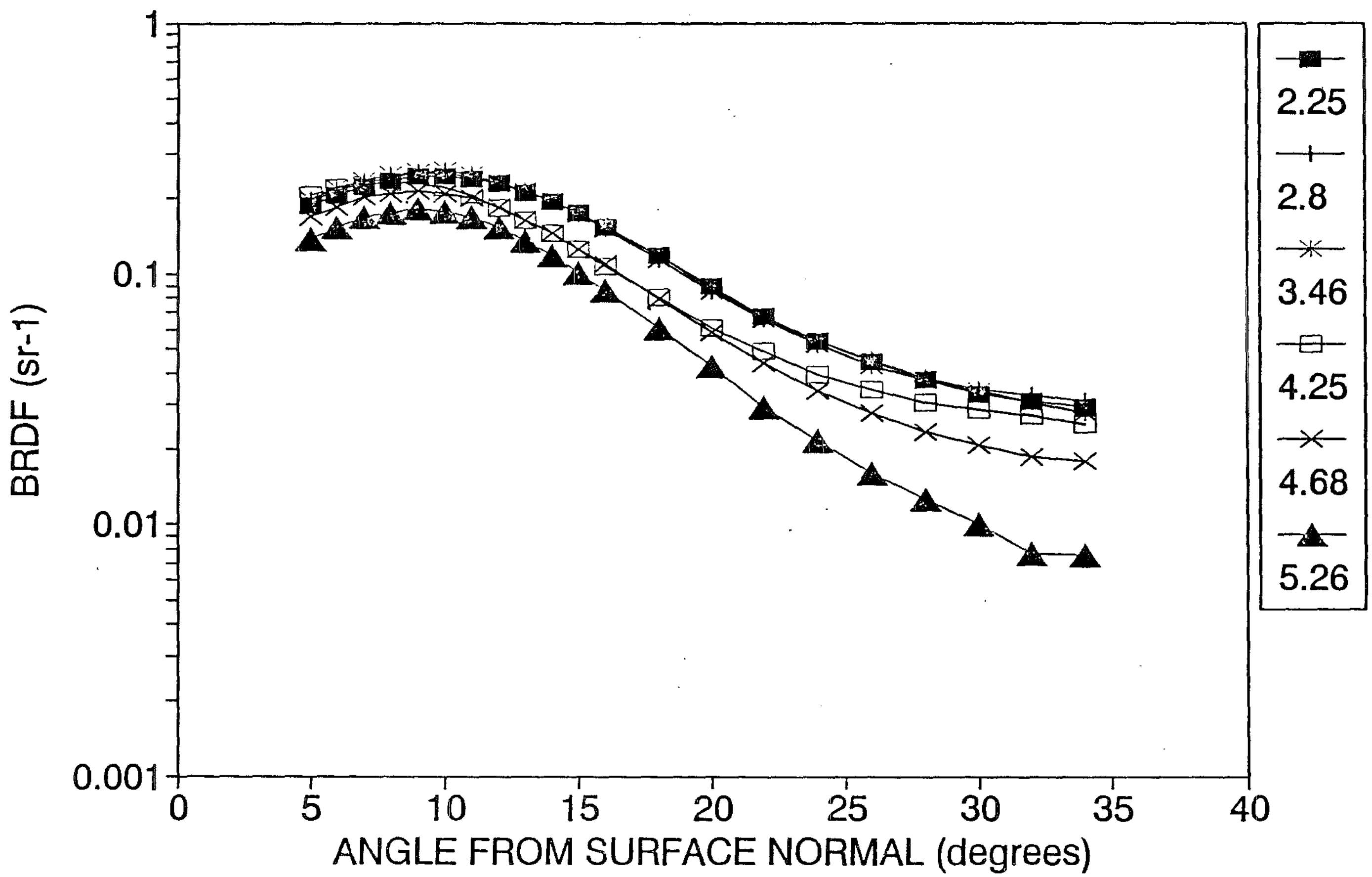
UNFLOWN BLACK LEFT
(Multiple Wavelengths)



FLOWN BLACK LEFT
(Multiple Wavelengths)



FLOWN BLACK RIGHT
(Multiple Wavelengths)



FILE: UNWHITEL.WQ1
SAMPLE: UNFLOWN WHITE LEFT
DIFFUSE STANDARD: ALUMINUM DIFFUSER
INCIDENCE ANGLE = 9 degrees
NOTE: ANGLE MEASURED FROM SURFACE NORMAL

ANGLE (DEG)	RUN 17 BB	RUN 27 2.27	RUN 37 2.49	RUN 47 2.81	RUN 57 3.46	RUN 67 4.25	RUN 77 4.68	RUN 87 5.26	RUN 97 BB
5	0.124	0.235	0.225	0.095	0.108	0.083	0.055	0.037	0.122
6	0.126	0.236	0.226	0.097	0.110	0.086	0.056	0.039	0.124
7	0.127	0.237	0.227	0.098	0.112	0.086	0.057	0.039	0.125
8	0.127	0.237	0.229	0.098	0.113	0.086	0.058	0.040	0.126
9	0.127	0.237	0.229	0.098	0.112	0.087	0.058	0.040	0.126
10	0.127	0.237	0.228	0.099	0.112	0.087	0.058	0.040	0.126
11	0.126	0.236	0.228	0.098	0.111	0.087	0.058	0.040	0.125
12	0.126	0.235	0.227	0.097	0.110	0.087	0.057	0.039	0.124
13	0.124	0.233	0.225	0.096	0.110	0.085	0.055	0.038	0.123
14	0.122	0.231	0.223	0.095	0.107	0.083	0.054	0.036	0.121
15	0.121	0.230	0.222	0.093	0.106	0.082	0.052	0.035	0.119
16	0.118	0.228	0.220	0.091	0.104	0.081	0.050	0.033	0.117
18	0.114	0.224	0.215	0.087	0.100	0.076	0.046	0.029	0.113
20	0.110	0.219	0.211	0.082	0.094	0.071	0.042	0.026	0.109
22	0.105	0.215	0.205	0.078	0.088	0.066	0.038	0.022	0.105
24	0.100	0.210	0.201	0.073	0.084	0.063	0.034	0.019	0.100
26	0.097	0.206	0.197	0.069	0.081	0.058	0.031	0.016	0.097
28	0.094	0.203	0.193	0.066	0.076	0.055	0.028	0.014	0.094
30	0.091	0.199	0.191	0.063	0.074	0.054	0.025	0.012	0.091
32	0.088	0.197	0.188	0.061	0.072	0.050	0.024	0.010	0.089
34	0.086	0.195	0.186	0.059	0.071	0.049	0.022	0.009	0.087

FILE: UNWHITER.WQ1
SAMPLE: UNFLOWN WHITE RIGHT
DIFFUSE STANDARD: ALUMINUM DIFFUSER
INCIDENCE ANGLE = 9 degrees
NOTE: ANGLE MEASURED FROM SURFACE NORMAL

ANGLE (DEG)	RUN 18 BB	RUN 28 2.27	RUN 38 2.49	RUN 48 2.81	RUN 58 3.46	RUN 68 4.25	RUN 78 4.68	RUN 88 5.26	RUN 98 BB
5	0.125	0.235	0.226	0.105	0.114	0.085	0.057	0.041	0.126
6	0.127	0.236	0.228	0.106	0.116	0.086	0.058	0.042	0.127
7	0.128	0.238	0.229	0.107	0.116	0.088	0.060	0.044	0.129
8	0.129	0.239	0.229	0.108	0.117	0.089	0.061	0.044	0.130
9	0.128	0.238	0.229	0.108	0.117	0.090	0.060	0.044	0.130
10	0.128	0.238	0.228	0.107	0.117	0.089	0.060	0.044	0.129
11	0.128	0.237	0.228	0.108	0.117	0.089	0.060	0.043	0.128
12	0.126	0.236	0.227	0.107	0.116	0.089	0.059	0.042	0.127
13	0.125	0.234	0.225	0.104	0.114	0.086	0.057	0.041	0.126
14	0.123	0.232	0.223	0.103	0.112	0.084	0.055	0.040	0.124
15	0.121	0.230	0.221	0.100	0.108	0.081	0.053	0.037	0.122
16	0.118	0.228	0.219	0.098	0.106	0.078	0.051	0.035	0.119
18	0.113	0.222	0.213	0.093	0.101	0.073	0.046	0.030	0.114
20	0.108	0.216	0.208	0.088	0.094	0.068	0.041	0.027	0.108
22	0.103	0.210	0.202	0.083	0.091	0.062	0.036	0.023	0.104
24	0.099	0.206	0.197	0.078	0.085	0.059	0.032	0.020	0.100
26	0.094	0.202	0.191	0.073	0.081	0.055	0.028	0.016	0.096
28	0.091	0.197	0.188	0.069	0.077	0.051	0.025	0.014	0.092
30	0.089	0.195	0.185	0.067	0.073	0.049	0.023	0.011	0.089
32	0.087	0.192	0.184	0.064	0.071	0.047	0.021	0.010	0.087
34	0.084	0.190	0.180	0.062	0.069	0.045	0.020	0.009	0.085

FILE: WHITEL.WQ1
SAMPLE: FLOWN WHITE LEFT
DIFFUSE STANDARD: ALUMINUM DIFFUSER
INCIDENCE ANGLE = 9 degrees
NOTE: ANGLE MEASURED FROM SURFACE NORMAL

ANGLE (DEG)	RUN 19 BB	RUN 29 2.27	RUN 39 2.49	RUN 49 2.81	RUN 59 3.46	RUN 69 4.25	RUN 79 4.68	RUN 89 5.26	RUN 99 BB
5	0.119	0.226	0.217	0.077	0.119	0.094	0.060	0.036	0.123
6	0.121	0.228	0.219	0.079	0.121	0.096	0.062	0.038	0.124
7	0.122	0.228	0.219	0.079	0.121	0.098	0.063	0.039	0.125
8	0.124	0.228	0.219	0.080	0.121	0.099	0.064	0.040	0.126
9	0.125	0.229	0.220	0.081	0.122	0.099	0.064	0.040	0.126
10	0.126	0.229	0.221	0.081	0.122	0.099	0.064	0.041	0.126
11	0.124	0.228	0.220	0.081	0.122	0.099	0.064	0.041	0.126
12	0.123	0.227	0.220	0.080	0.121	0.100	0.063	0.040	0.125
13	0.121	0.227	0.219	0.079	0.120	0.099	0.063	0.039	0.124
14	0.120	0.226	0.217	0.078	0.120	0.096	0.061	0.038	0.123
15	0.120	0.225	0.216	0.076	0.118	0.094	0.060	0.036	0.122
16	0.118	0.223	0.214	0.075	0.117	0.093	0.058	0.034	0.120
18	0.115	0.220	0.212	0.072	0.111	0.089	0.053	0.031	0.116
20	0.110	0.216	0.208	0.068	0.108	0.084	0.049	0.026	0.111
22	0.107	0.213	0.204	0.064	0.104	0.080	0.046	0.023	0.108
24	0.104	0.210	0.200	0.060	0.100	0.076	0.042	0.020	0.104
26	0.101	0.206	0.197	0.056	0.095	0.073	0.039	0.017	0.100
28	0.098	0.204	0.194	0.054	0.092	0.069	0.035	0.014	0.098
30	0.096	0.202	0.192	0.052	0.090	0.067	0.033	0.013	0.096
32	0.094	0.199	0.190	0.050	0.087	0.066	0.031	0.011	0.093
34	0.090	0.198	0.188	0.047	0.087	0.064	0.030	0.010	0.092

FILE: WHITER.WQ1
SAMPLE: FLOWN WHITE RIGHT
DIFFUSE STANDARD: ALUMINUM DIFFUSER
INCIDENCE ANGLE = 9 degrees
NOTE: ANGLE MEASURED FROM SURFACE NORMAL

ANGLE (DEG)	RUN 20 BB	RUN 30 2.27	RUN 40 2.49	RUN 50 2.81	RUN 60 3.46	RUN 70 4.25	RUN 80 4.68	RUN 90 5.26	RUN 100 BB
5	0.122	0.226	0.217	0.078	0.119	0.094	0.061	0.036	0.123
6	0.123	0.227	0.219	0.080	0.121	0.096	0.062	0.038	0.124
7	0.124	0.227	0.220	0.081	0.123	0.097	0.063	0.039	0.125
8	0.124	0.228	0.220	0.081	0.123	0.098	0.063	0.040	0.125
9	0.125	0.228	0.221	0.081	0.123	0.099	0.063	0.040	0.125
10	0.124	0.228	0.220	0.081	0.123	0.099	0.063	0.039	0.125
11	0.124	0.227	0.218	0.081	0.123	0.097	0.063	0.040	0.124
12	0.123	0.226	0.218	0.080	0.122	0.098	0.062	0.038	0.123
13	0.122	0.225	0.218	0.079	0.118	0.096	0.061	0.036	0.122
14	0.121	0.223	0.217	0.078	0.118	0.093	0.059	0.035	0.121
15	0.119	0.222	0.215	0.075	0.117	0.092	0.058	0.034	0.119
16	0.117	0.221	0.212	0.075	0.114	0.091	0.056	0.032	0.118
18	0.114	0.217	0.209	0.070	0.110	0.085	0.051	0.028	0.113
20	0.110	0.214	0.206	0.066	0.106	0.083	0.047	0.025	0.110
22	0.105	0.210	0.202	0.063	0.103	0.079	0.043	0.021	0.106
24	0.103	0.207	0.198	0.059	0.098	0.074	0.040	0.019	0.102
26	0.099	0.203	0.195	0.056	0.094	0.072	0.037	0.016	0.100
28	0.097	0.200	0.192	0.053	0.092	0.069	0.034	0.014	0.096
30	0.096	0.198	0.190	0.050	0.089	0.067	0.032	0.012	0.094
32	0.093	0.196	0.187	0.049	0.087	0.065	0.030	0.011	0.093
34	0.091	0.194	0.186	0.048	0.084	0.063	0.029	0.009	0.091

FILE: UNBLACKL.WQ1
SAMPLE: UNFLOWN BLACK LEFT
DIFFUSE STANDARD: ALUMINUM DIFFUSER
INCIDENCE ANGLE = 9 degrees
NOTE: ANGLE MEASURED FROM SURFACE NORMAL

ANGLE (DEG)	RUN 21 BB	RUN 31 2.27	RUN 41 2.49	RUN 51 2.81	RUN 61 3.46	RUN 71 4.25	RUN 81 4.68	RUN 91 5.26	RUN 101 BB
5	0.430	0.443	0.518	0.513	0.600	0.622	0.474	0.379	0.625
6	0.524	0.542	0.623	0.619	0.708	0.695	0.575	0.477	0.694
7	0.599	0.624	0.705	0.695	0.774	0.694	0.635	0.542	0.713
8	0.635	0.669	0.740	0.721	0.773	0.628	0.633	0.552	0.663
9	0.614	0.670	0.724	0.698	0.721	0.525	0.563	0.488	0.575
10	0.551	0.625	0.665	0.628	0.617	0.409	0.466	0.398	0.462
11	0.464	0.549	0.570	0.530	0.492	0.312	0.355	0.297	0.351
12	0.365	0.451	0.460	0.420	0.379	0.229	0.266	0.218	0.262
13	0.278	0.354	0.354	0.320	0.277	0.167	0.191	0.157	0.190
14	0.205	0.267	0.265	0.237	0.203	0.120	0.138	0.111	0.136
15	0.147	0.197	0.192	0.172	0.147	0.090	0.100	0.079	0.098
16	0.107	0.145	0.141	0.125	0.108	0.066	0.073	0.056	0.072
18	0.059	0.079	0.078	0.069	0.061	0.042	0.041	0.029	0.042
20	0.036	0.048	0.047	0.043	0.041	0.031	0.027	0.017	0.028
22	0.026	0.033	0.033	0.031	0.031	0.025	0.020	0.011	0.022
24	0.021	0.027	0.028	0.026	0.025	0.023	0.016	0.008	0.019
26	0.018	0.023	0.023	0.023	0.022	0.020	0.014	0.006	0.017
28	0.016	0.021	0.021	0.021	0.022	0.019	0.013	0.005	0.016
30	0.015	0.020	0.021	0.020	0.021	0.019	0.012	0.004	0.015
32	0.014	0.019	0.020	0.019	0.020	0.018	0.012	0.004	0.015
34	0.014	0.018	0.020	0.019	0.019	0.017	0.012	0.004	0.014

FILE: BLACKL.WQ1
SAMPLE: FLOWN BLACK LEFT
DIFFUSE STANDARD: ALUMINUM DIFFUSER
INCIDENCE ANGLE = 9 degrees
NOTE: ANGLE MEASURED FROM SURFACE NORMAL

ANGLE (DEG)	RUN 22 BB	RUN 32 2.27	RUN 42 2.49	RUN 52 2.81	RUN 62 3.46	RUN 72 4.25	RUN 82 4.68	RUN 92 5.26	RUN 102 BB
5	0.186	0.186	0.212	0.196	0.206	0.197	0.166	0.139	0.197
6	0.200	0.203	0.228	0.215	0.223	0.215	0.182	0.154	0.210
7	0.213	0.220	0.239	0.232	0.236	0.224	0.195	0.165	0.221
8	0.221	0.228	0.249	0.239	0.247	0.233	0.205	0.174	0.226
9	0.223	0.237	0.248	0.247	0.252	0.230	0.208	0.177	0.224
10	0.219	0.239	0.243	0.246	0.248	0.221	0.205	0.172	0.216
11	0.211	0.233	0.233	0.238	0.239	0.205	0.199	0.164	0.203
12	0.195	0.222	0.219	0.227	0.225	0.184	0.183	0.151	0.186
13	0.177	0.209	0.200	0.211	0.207	0.167	0.166	0.134	0.166
14	0.158	0.192	0.179	0.192	0.184	0.145	0.147	0.117	0.147
15	0.137	0.173	0.159	0.171	0.163	0.122	0.128	0.100	0.127
16	0.119	0.153	0.139	0.151	0.141	0.109	0.110	0.085	0.110
18	0.089	0.117	0.105	0.112	0.107	0.080	0.081	0.060	0.081
20	0.066	0.088	0.079	0.086	0.080	0.060	0.058	0.042	0.060
22	0.050	0.067	0.061	0.065	0.062	0.047	0.044	0.029	0.046
24	0.039	0.052	0.049	0.051	0.050	0.039	0.034	0.020	0.037
26	0.032	0.043	0.042	0.043	0.041	0.034	0.027	0.015	0.031
28	0.027	0.037	0.036	0.037	0.034	0.029	0.023	0.012	0.027
30	0.025	0.033	0.034	0.034	0.032	0.027	0.020	0.010	0.024
32	0.023	0.030	0.031	0.031	0.031	0.026	0.019	0.008	0.023
34	0.021	0.028	0.029	0.030	0.029	0.025	0.018	0.007	0.022

FILE: BLACKR.WQ1
SAMPLE: FLOWN BLACK RIGHT
DIFFUSE STANDARD: ALUMINUM DIFFUSER
INCIDENCE ANGLE = 9 degrees
NOTE: ANGLE MEASURED FROM SURFACE NORMAL

ANGLE (DEG)	RUN 23 BB	RUN 33 2.27	RUN 43 2.49	RUN 53 2.81	RUN 63 3.46	RUN 73 4.25	RUN 83 4.68	RUN 93 5.26	RUN 103 BB
5	0.166	0.188	0.193	0.196	0.199	0.206	0.168	0.138	0.190
6	0.185	0.207	0.211	0.215	0.219	0.221	0.185	0.153	0.208
7	0.202	0.223	0.229	0.231	0.236	0.227	0.203	0.169	0.221
8	0.216	0.236	0.245	0.244	0.250	0.234	0.209	0.176	0.229
9	0.222	0.245	0.255	0.251	0.257	0.231	0.214	0.182	0.229
10	0.225	0.244	0.254	0.252	0.257	0.221	0.210	0.178	0.224
11	0.218	0.238	0.250	0.244	0.248	0.205	0.199	0.168	0.211
12	0.208	0.229	0.241	0.233	0.234	0.181	0.184	0.153	0.195
13	0.192	0.212	0.225	0.216	0.215	0.163	0.165	0.136	0.176
14	0.174	0.195	0.205	0.195	0.195	0.145	0.146	0.119	0.156
15	0.155	0.175	0.182	0.175	0.173	0.126	0.126	0.101	0.136
16	0.136	0.154	0.163	0.155	0.151	0.107	0.110	0.086	0.119
18	0.103	0.119	0.126	0.117	0.114	0.081	0.080	0.060	0.088
20	0.076	0.089	0.094	0.088	0.085	0.061	0.058	0.043	0.065
22	0.057	0.068	0.073	0.066	0.066	0.049	0.044	0.030	0.050
24	0.045	0.054	0.057	0.054	0.052	0.040	0.034	0.022	0.040
26	0.036	0.045	0.047	0.045	0.043	0.035	0.028	0.016	0.033
28	0.031	0.038	0.041	0.038	0.038	0.030	0.023	0.013	0.028
30	0.027	0.033	0.035	0.035	0.034	0.028	0.021	0.010	0.026
32	0.025	0.031	0.033	0.033	0.031	0.027	0.018	0.008	0.024
34	0.023	0.029	0.032	0.031	0.028	0.025	0.018	0.008	0.022